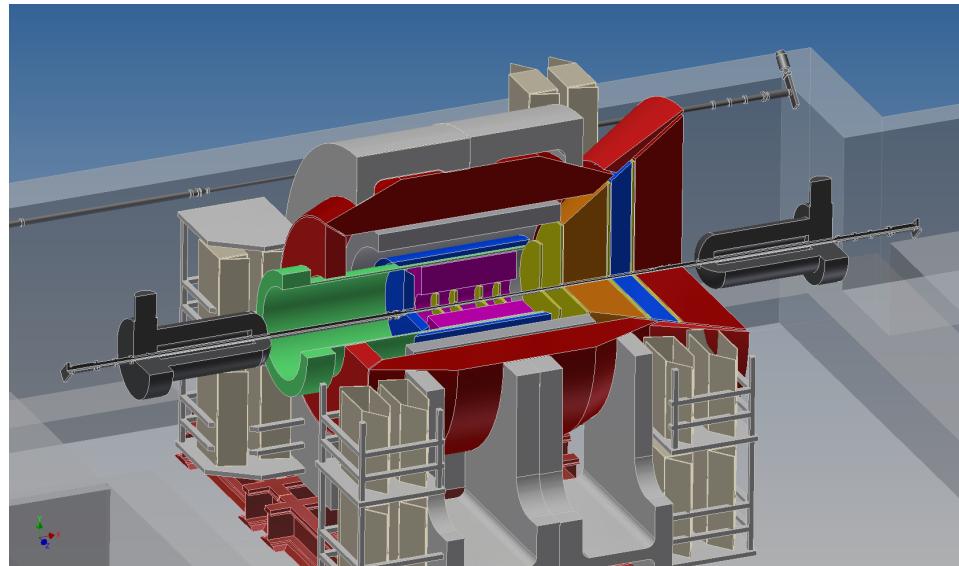




Detector Performance and Physics Capabilities



A.Bazilevsky
for PHENIX/ePHENIX

EIC Physics

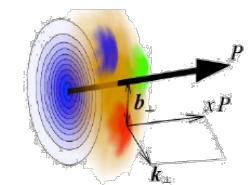
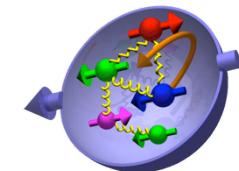
EIC White Paper:
arXiv:12.12.1701

Distribution of quarks and gluons and their spins in space and momentum inside the nucleon

Nucleon helicity structure

Parton transverse motion in the nucleon

Spacial distribution of partons and parton orbital angular momentum

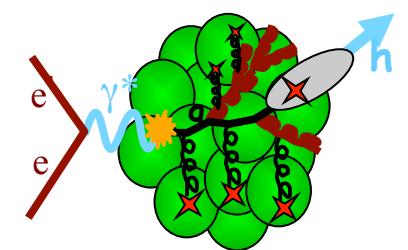


QCD in nuclei

Nuclear modification of parton distributions

Gluon saturation

Propagation/Hadronization in nuclear matter



~~Weak interactions & beyond standard model~~

Require highest energy and lum. -> not for stage-1

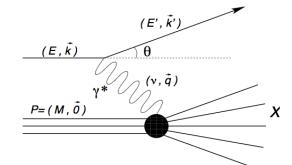
General Detector Concept

See K. Boyle talk

Inclusive DIS and scattered electron measurements

With focus in e-going direction and barrel

High resolution EMCAL and tracking; minimal material budget

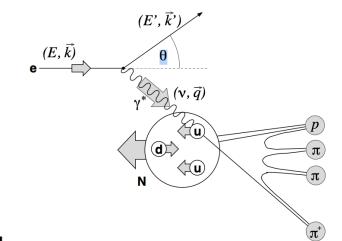


Semi-inclusive DIS and hadron ID

With focus in h-going direction and barrel

Barrel: DIRC for $p_h < 4$ GeV/c

h-going direction: aerogel for lower p_h and gas RICH for higher p_h

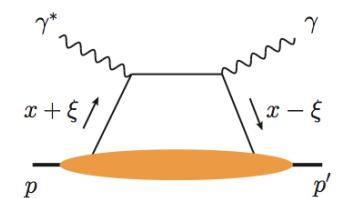


Exclusive DIS (DVCS etc.)

EMCAL and tracking coverage in $-4 < \eta < 4$

High granularity EMCAL in e-going direction

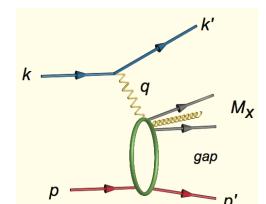
Roman Pots in h-going direction



Diffractive

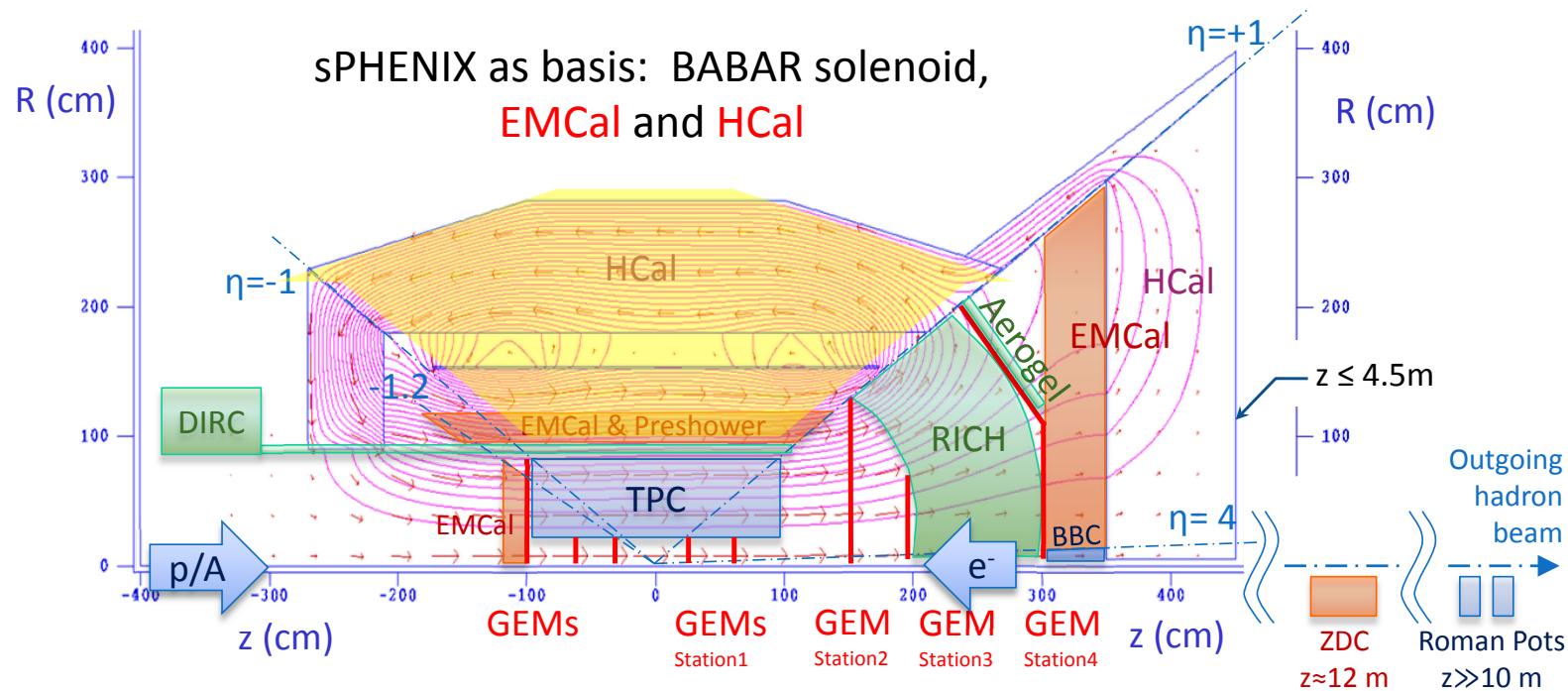
Rapidity gap measurements: HCal in $-1 < \eta < 5$; EMCAL in $-4 < \eta < 4$

ZDC in h-going direction



ePHENIX Detector Concept

See K. Boyle talk

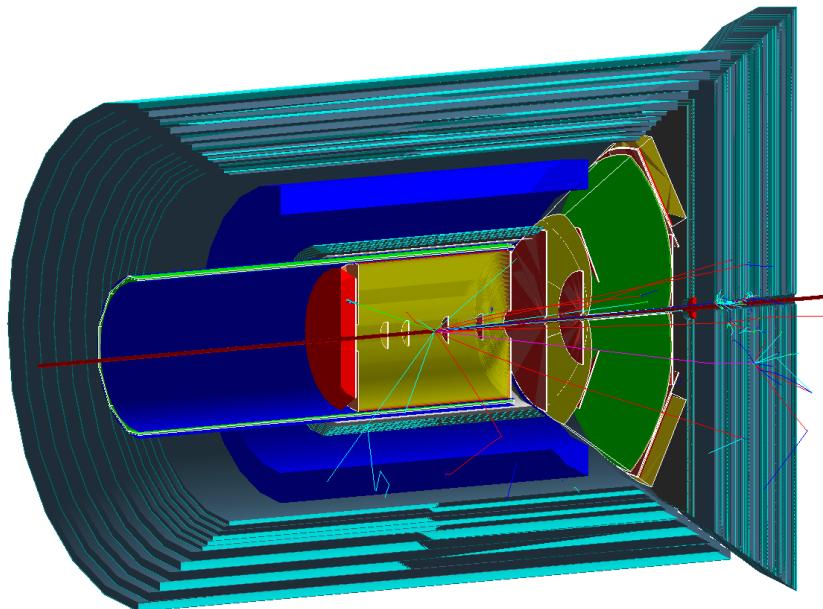


- $-4 < \eta < -1$ (e-going):
 - Crystal calorimeter with high energy and position resolution
 - GEM Trackers
- $-1 < \eta < 1$ (barrel):
 - Add Compact-TPC and DIRC
- $1 < \eta < 4$ (h-going):
 - HCAL & EMCAL ($1 < \eta < 5$)
 - GEM Trackers
 - Aerogel RICH ($1 < \eta < 2$)
 - Gas RICH
- Far Forward (h-going)
 - ZDC and Roman Pots

ePHENIX performance evaluation

Generators:

PYTHIA, MILOU (for DVCS), **RAPGAP** (diffractive), **RADGEN** (rad. effects)
Thanks to BNL EIC group for maintaining them at racf



GEANT4 description of ePHENIX

Simulation and analysis software
common with sPHENIX and PHENIX

Experience from previous DIS experiments:

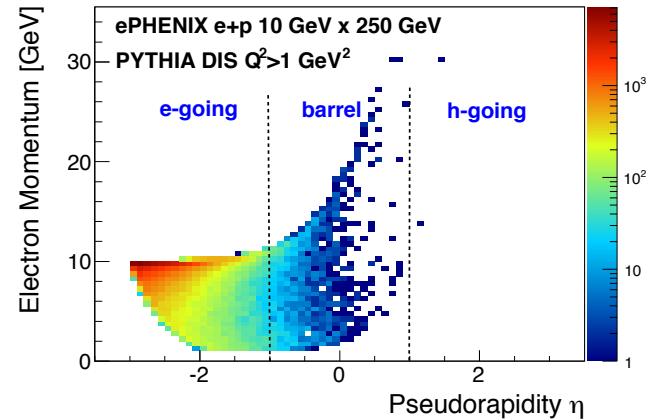
SLAC, CERN, DESY, Jlab

Also studies and developments from **BNL EIC** group

DIS kinematics

Measure scattered electron energy and angle:

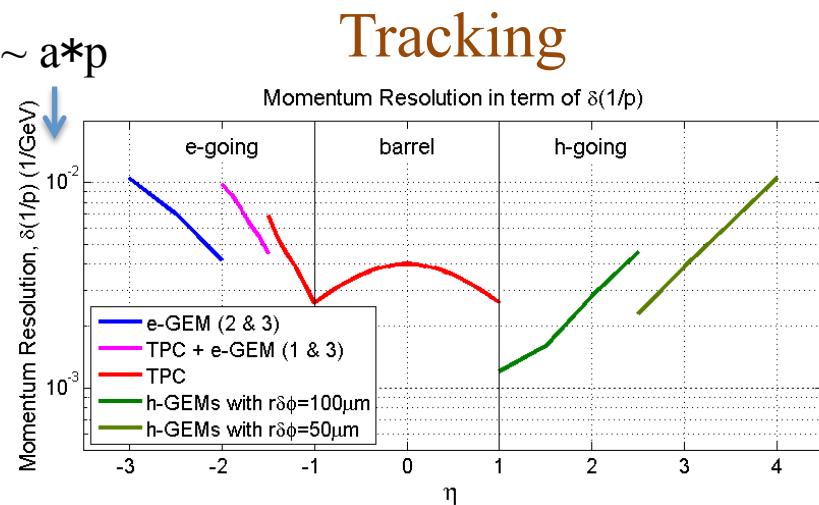
$$Q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right) \quad y = 1 - \frac{E'}{E} \cos^2\left(\frac{\theta}{2}\right) \quad x = \frac{Q^2}{sy}$$



- Endcap Calorimeter:
 - PbWO₄ crystal
 - $\sigma_E/E \sim 1.5\%/\sqrt{E}$
 - $\sigma_X < 3\text{mm}/\sqrt{E}$
- Barrel Calorimeter:
 - sPHENIX EMCal
 - Tungsten based
 - $\sigma_E/E \sim 12\%/\sqrt{E}$

Scattering mainly in e-going direction and barrel

$$\sigma_p/p \sim a * p$$



Inclusive DIS and Kinematics

eID and background rejection

Hadron rejection:

EMCal energy response and E/p

- ×20-30 at 1 GeV/c
- ×100 at 3 GeV/c

EMCal shower profile

Expect ×3-10

Not yet included in plots

EMCal long. segmentation and/or preshower

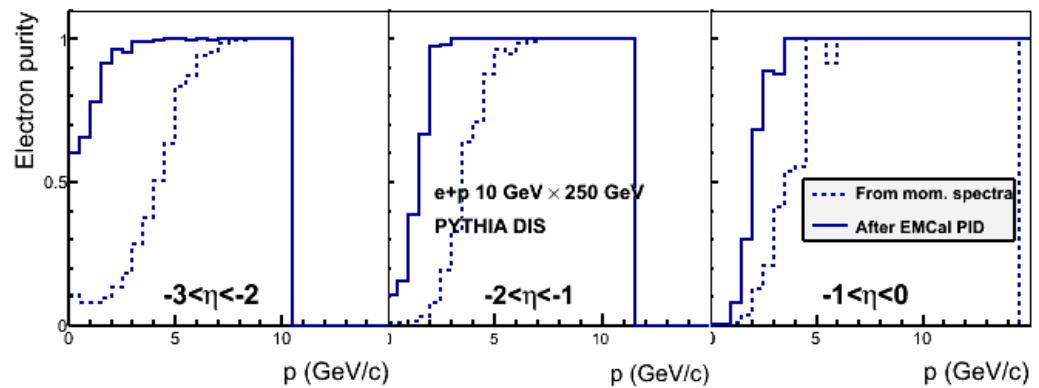
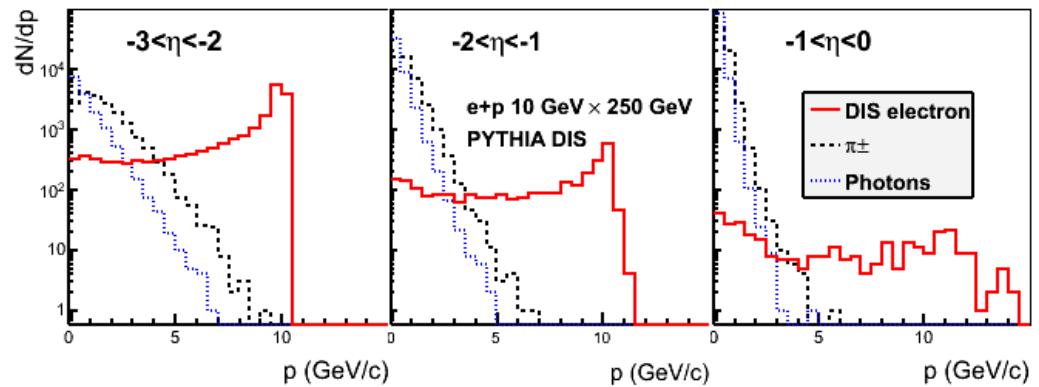
For future considerations

Photon rejection ($\gamma \rightarrow e^+e^-$)

Minimal material

Rejection with tracking and E/p

GEANT study is ongoing

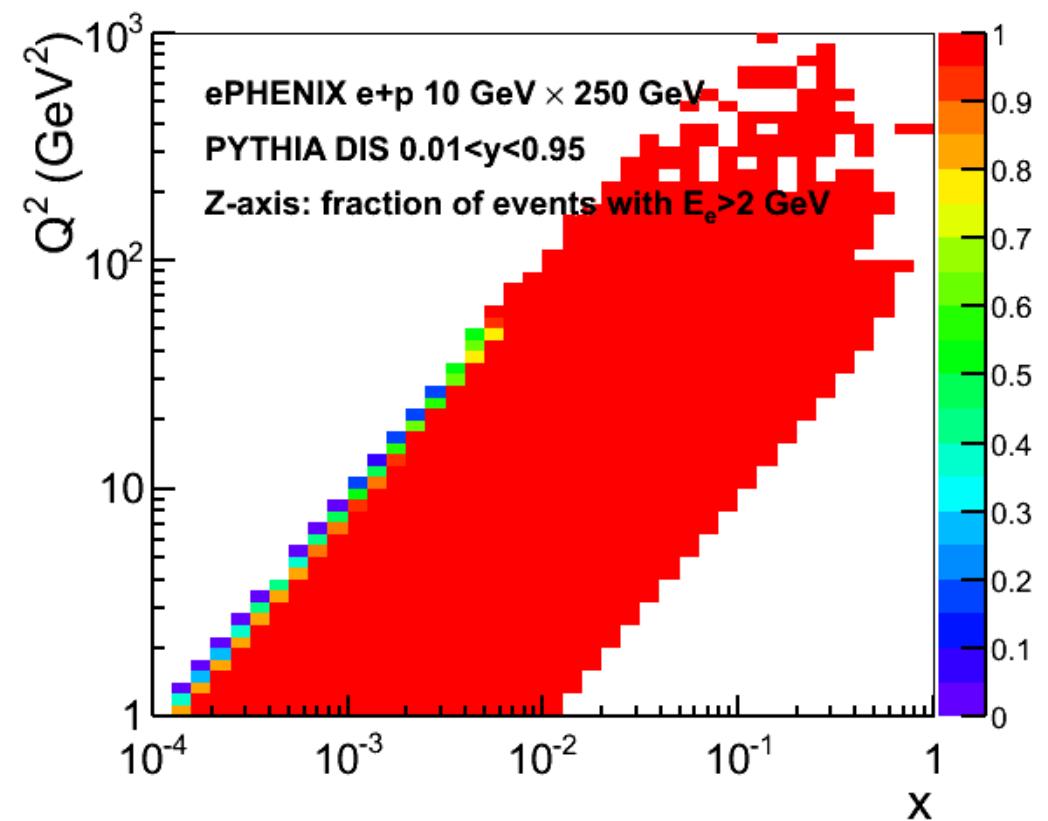


Reliable eID down to
p=2 GeV/c for 10 GeV e-beam
p=1 GeV/c for 5 GeV e-beam

Inclusive DIS and Kinematics

What if poor eID at $<2 \text{ GeV}/c$

Don't lose much of
the (x, Q^2) space



Inclusive DIS and Kinematics

Resolutions for (x, Q^2)

For perfect angle measurements:

$$\frac{\sigma_{Q^2}}{Q^2} = \frac{\sigma_{E'}}{E'} \quad \frac{\sigma_x}{x} = \frac{1}{y} \frac{\sigma_{E'}}{E'}$$

Defines the precision of unfolding technique to correct for smearing due to detector effects

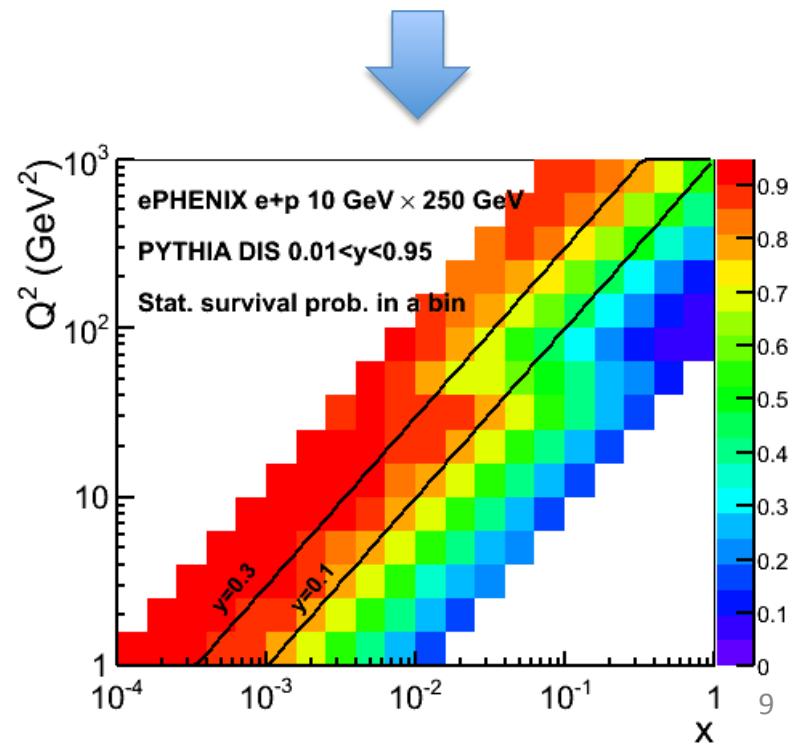
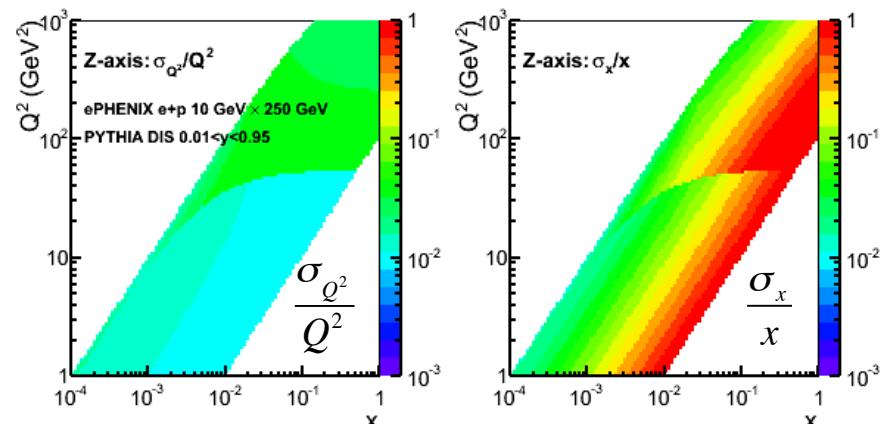
Results in statistics migration from bin to bin
 → bin survival probability

From HERMES experience: ~80% needed

Enough precision for scattered angle from EMCAL position resolution → no effect on bin survivability

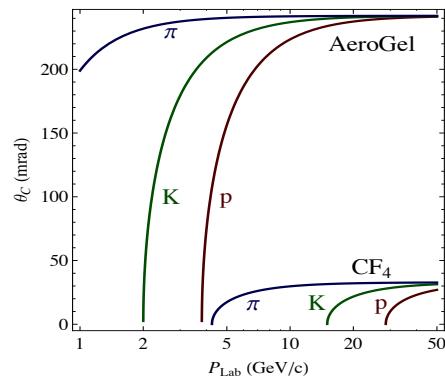
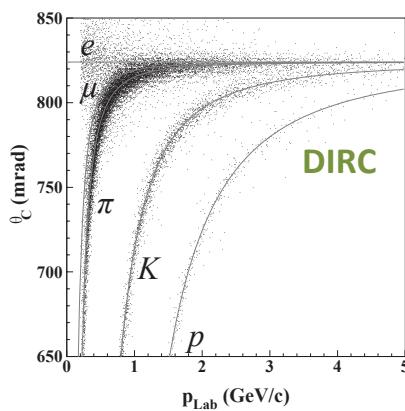
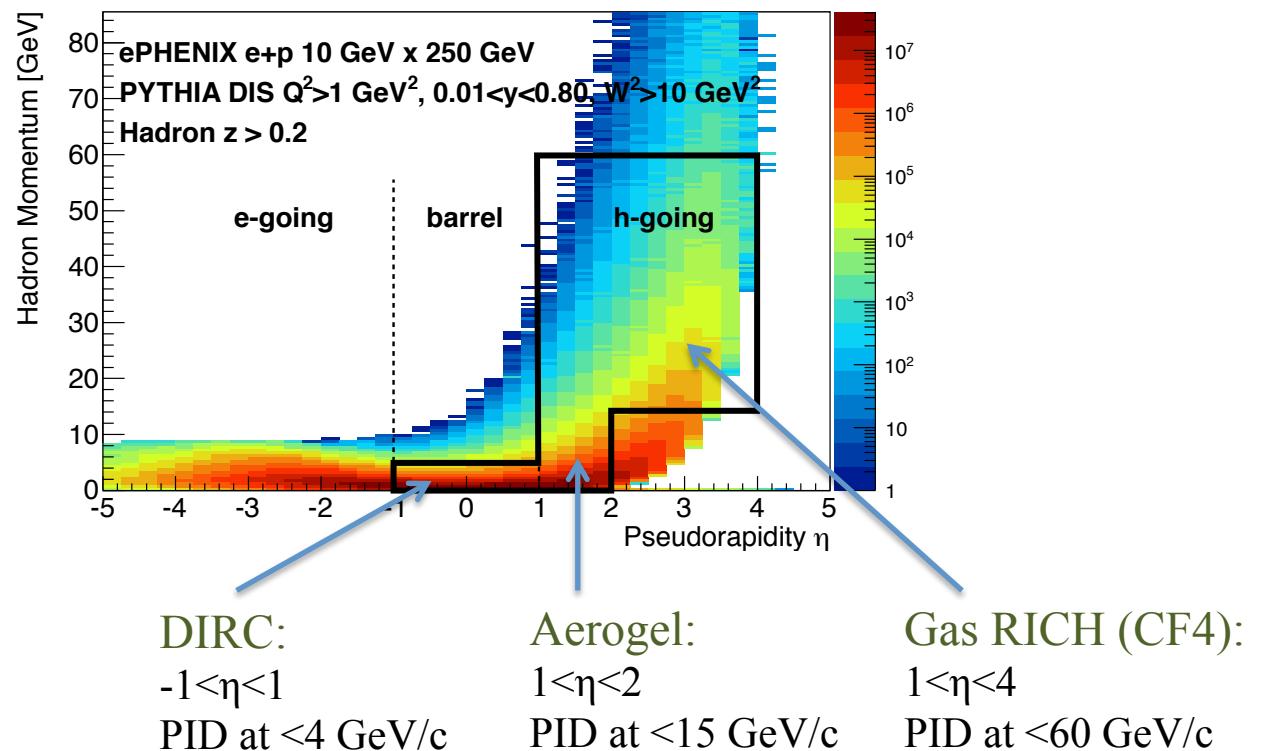
Jacquet-Blondel method (reconstruction with hadronic final state) will help at lower y and higher Q^2

Plan to exercise with full unfolding to quantify the detector and radiation effects



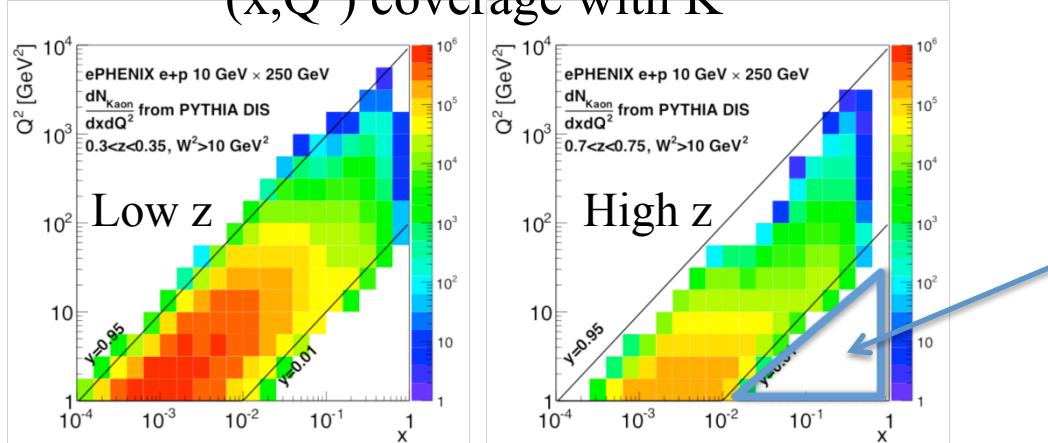
Semi-inclusive DIS and hadron ID

Focus on h-going direction and barrel



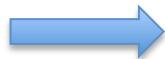
Semi-inclusive DIS and hadron ID

(x, Q^2) coverage with K

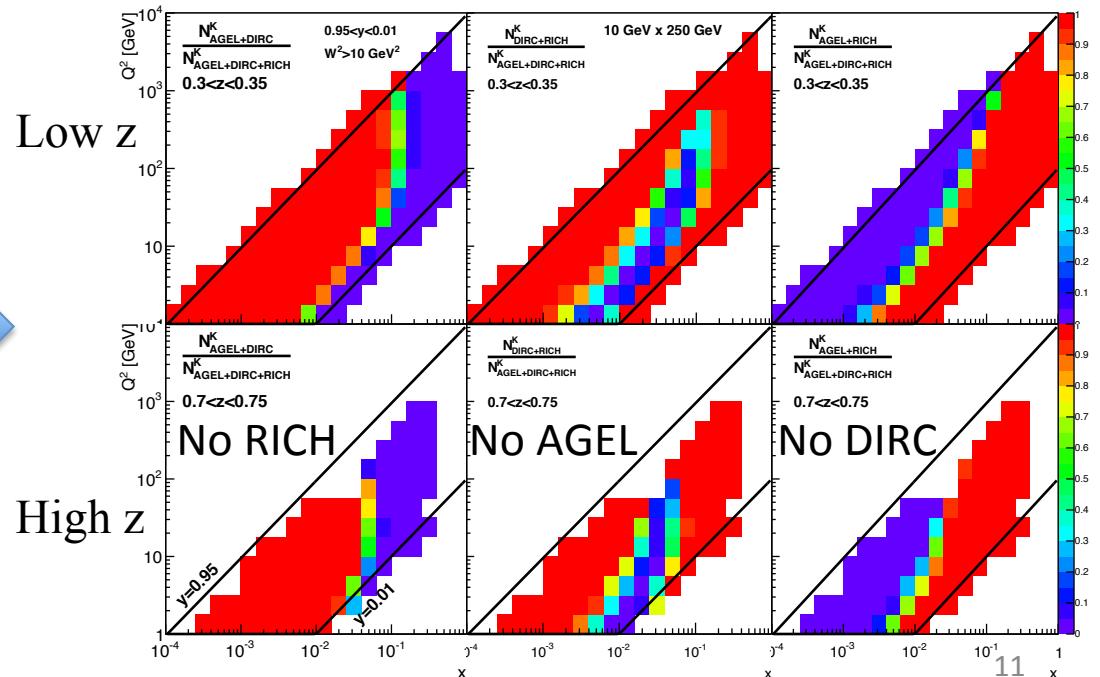


Coverage from fixed target polarized SIDIS
(HERMES, COMPASS, JLab)

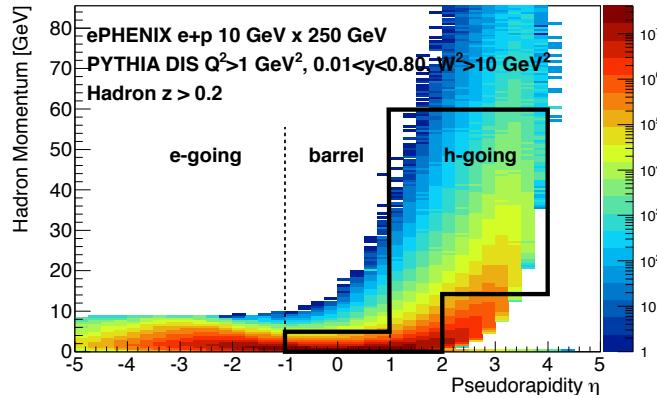
(x, Q^2) loss if not have given detector



All three detectors are important



Hadron ID with gas RICH



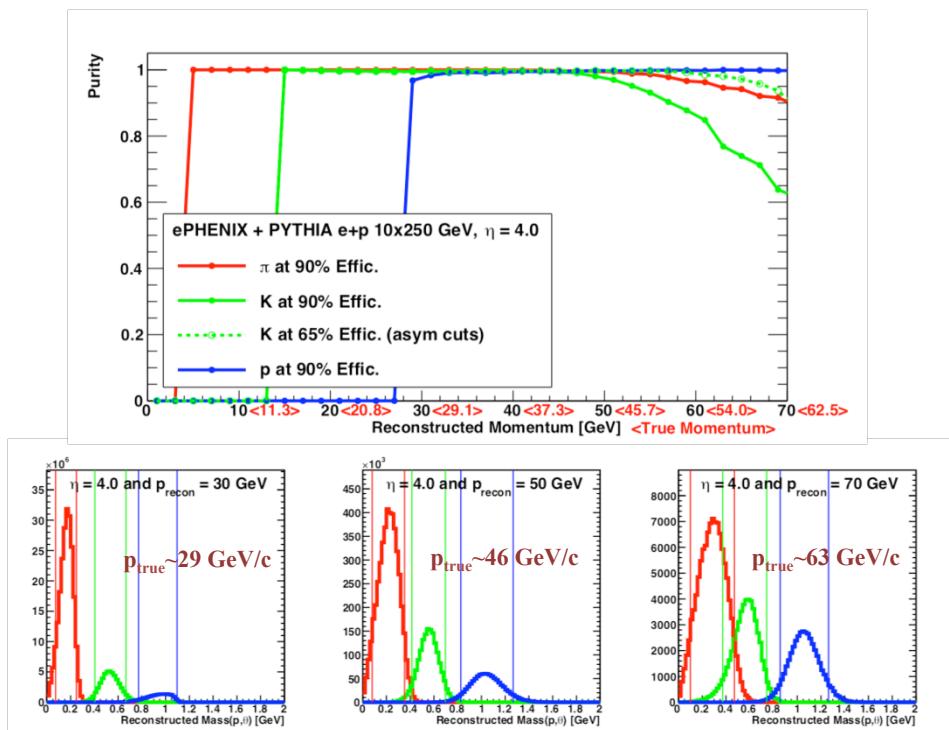
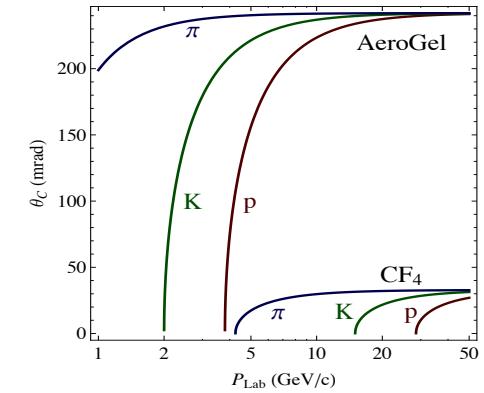
- PID up to ~ 60 GeV/c
- Currently limited by ring resolution (2.5% per photon - the current feedback from EIC R&D: see T.Hemmick presentation)
- Much smaller smearing due to magnetic field and off-center-vertex tracks: see J.Huang presentation

Gas RICH (CF4): $1 < \eta < 4$

Highest momentum measurements require:

- Good momentum resolution (combination of tracking and HCal)
- Good ring resolution

Need to balance efficiency and purity to get best measurement



Hadron measurements with HCal and Tracking

At very forward rapidity ($\eta \sim 4$) HCal energy resolution for single tracks may considerably exceed tracking momentum resolution

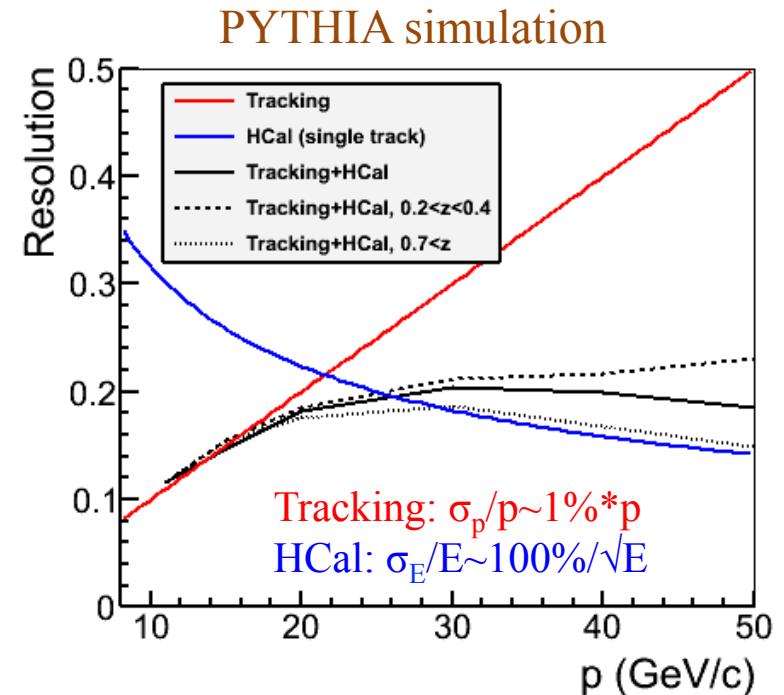
Can HCal be used to measure energy (momentum) of high momentum tracks ?

The main concern is that the energy depositions of tracks in vicinity of a given track are merged in a single cluster in HCal (non-separable in HCal)

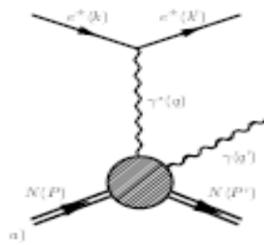
The idea:

Usual event structure is that there is one high momentum leading particle with a few lower momentum particles;

Low momentum particles are supposed to be well reconstructed with tracking, so their contribution in HCal can be evaluated and subtracted to calculate the energy deposition of the leading high momentum particle.



Full GEANT4 simulation is ongoing
The main impact is expected from tracking eff. and ghost (high momentum) tracks



Exclusive Measurements

DVCS:

Wide coverage for photon measurements

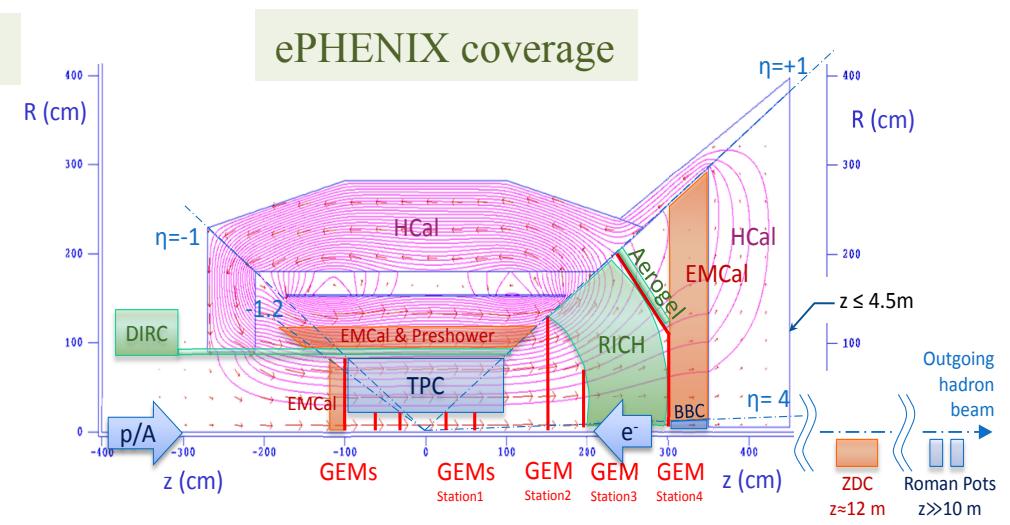
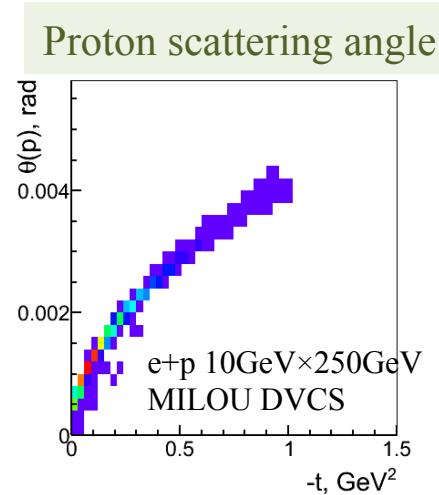
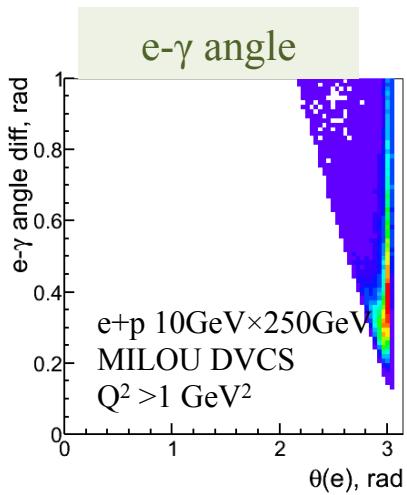
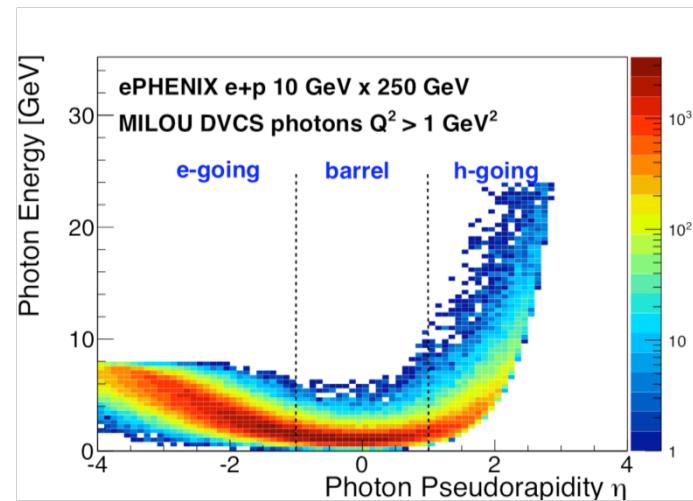
EMCal and tracking in $|\eta| < 4$

Separation of e- γ in EMCal

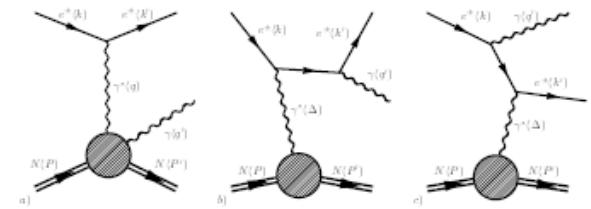
0.02×0.02 EMCal granularity is enough

Intact proton detection is highly desirable

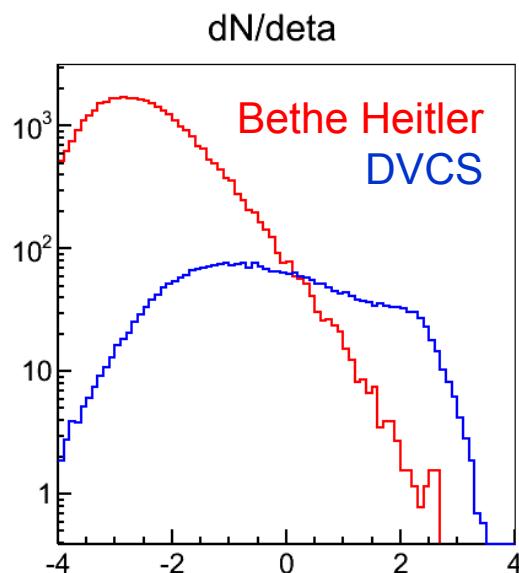
Roman Pots



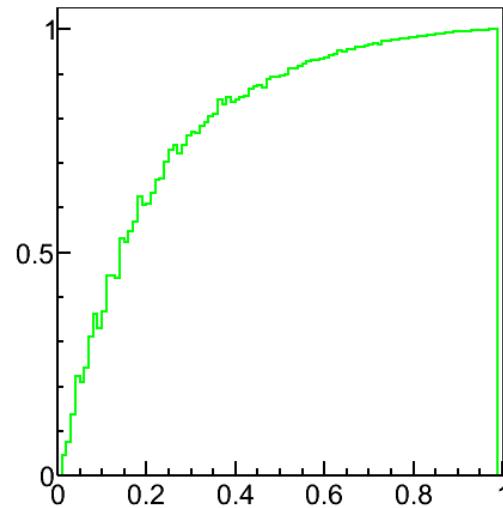
DVCS: reco



5 GeV (e) \times 250 GeV (p)



BH/(BH+DVCS) vs y



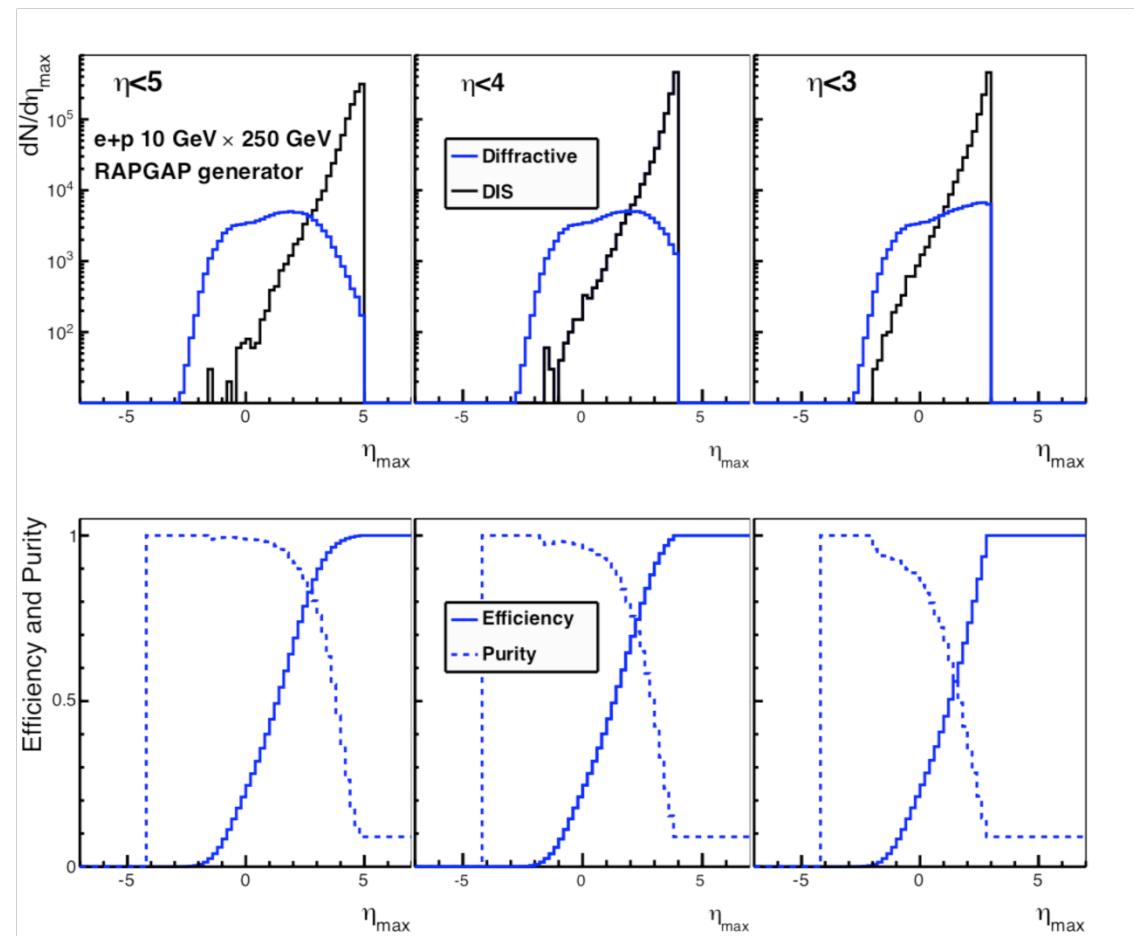
Central and forward regions are cleaner for DVCS

DVCS dominates at low y

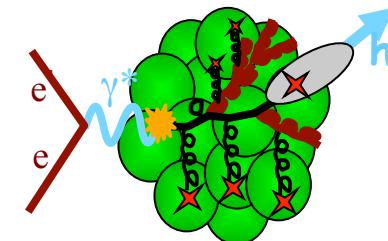
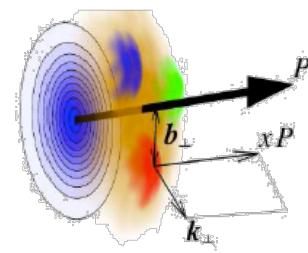
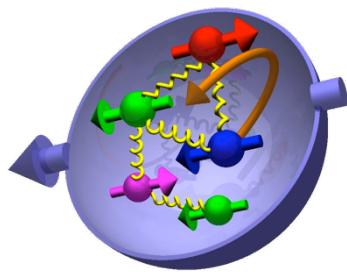
Wide kinematical coverage is crucial and is supported by ePHENIX design

Diffractive Measurements

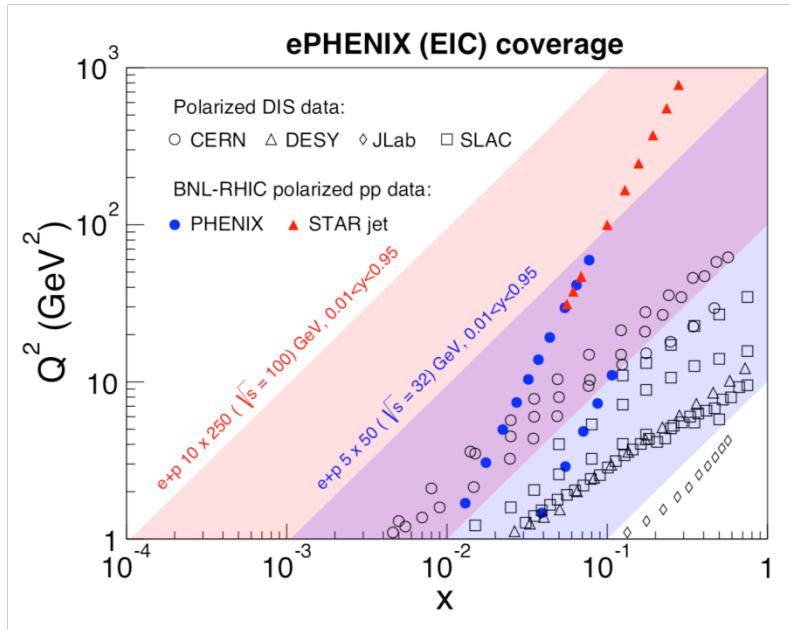
- Measure most forward going particle, to determine rapidity gap
 - HCal with $-1 < \eta < 5$ and EMCAL with $-4 < \eta < 4$ are excellent in separation of DIS and diffractive
- ZDC to measure nucleus breakup



Physics Expectations



Proton structure: long. spin



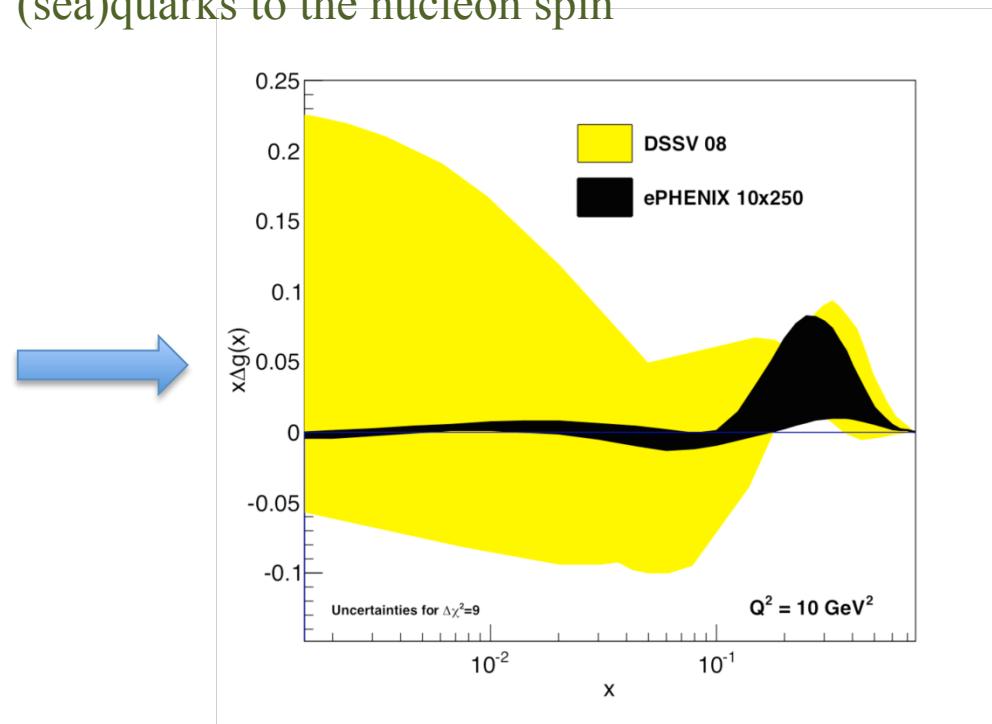
PHYTHIA generator and ePHENIX acceptance/efficiencies

10 fb^{-1} for 10×250 beams

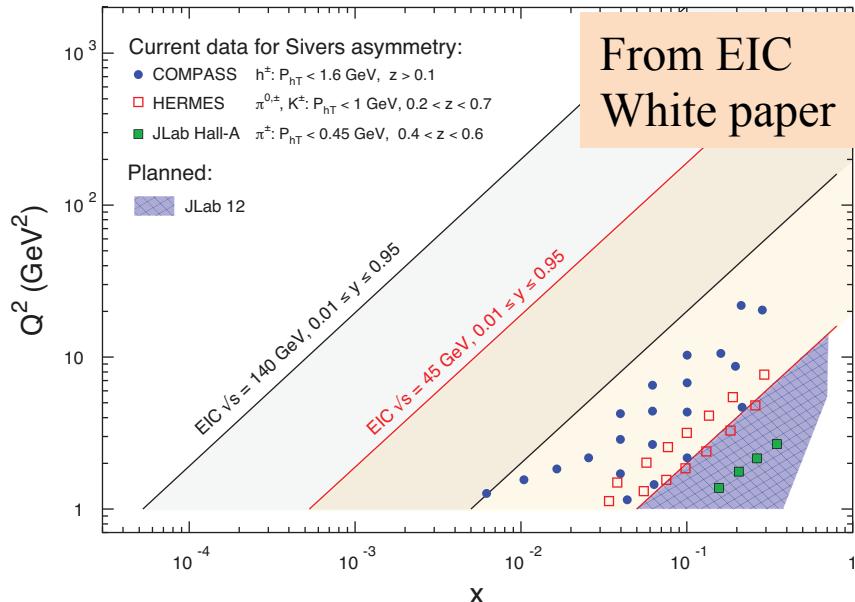
Inclusive and semi-inclusive DIS

Unique capability to reach much lower x and span a wider range in Q^2 (particularly important for gluon distributions)

=> Precise evaluation of the long. spin component of the gluons and flavor separated (sea)quarks to the nucleon spin



Motion of confined gluons and quarks



For the first time, determination of Sivers distributions over wide range in x will be possible

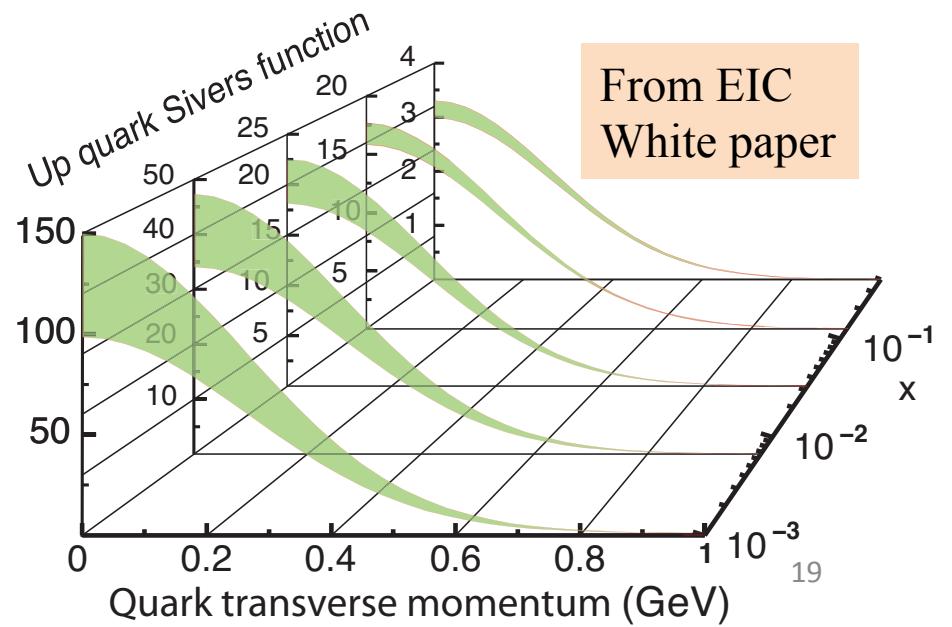
We're working on evaluation of expected Sivers constraint with ePHENIX data

Semi-inclusive DIS

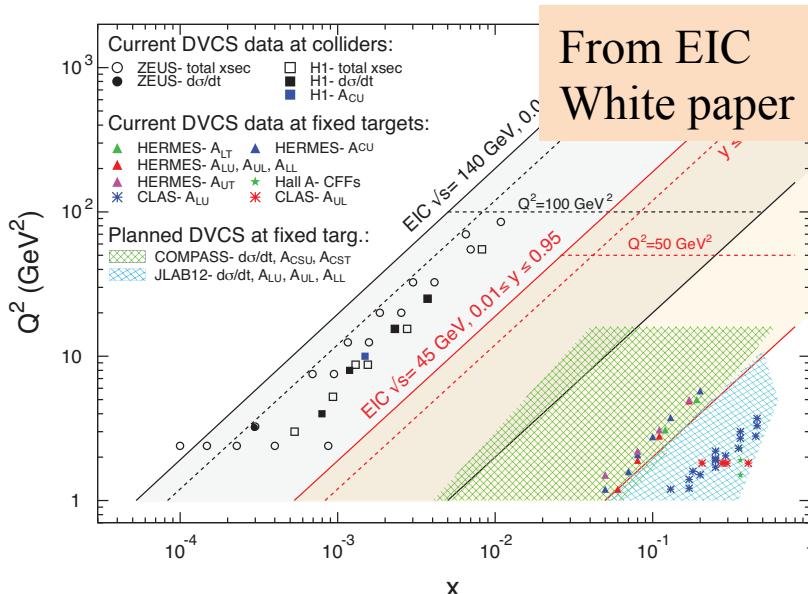
Transverse Momentum Distributions (Sivers)

Greatly expand x & Q^2 coverage

High luminosity \Rightarrow fully differential analysis over x, Q^2, z and P_{hT}



Proton Tomography



From EIC White paper

Exclusive DIS

Generalized Parton Distributions

Connected to parton orbital angular momentum

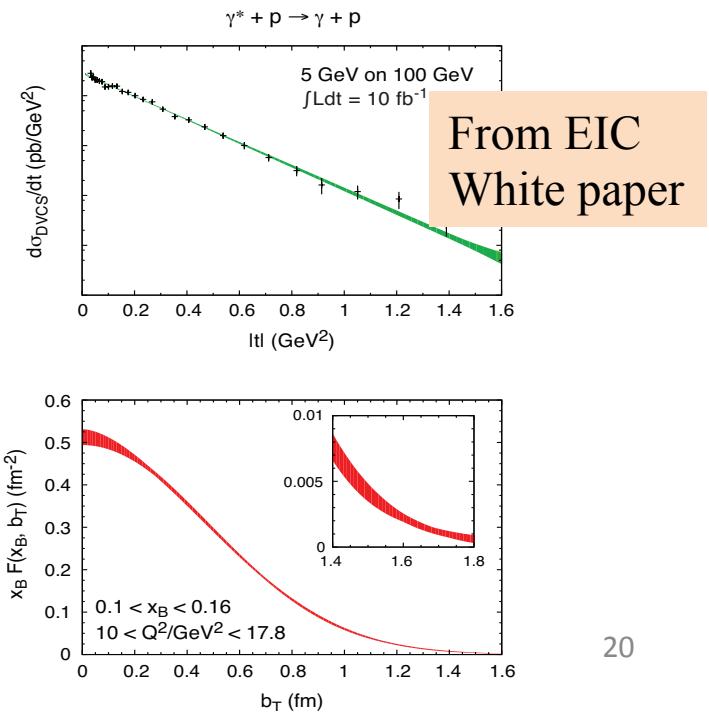
Existing data are either at low Q^2 or have sizable stat. uncertainties

Provide data in wide x&Q²

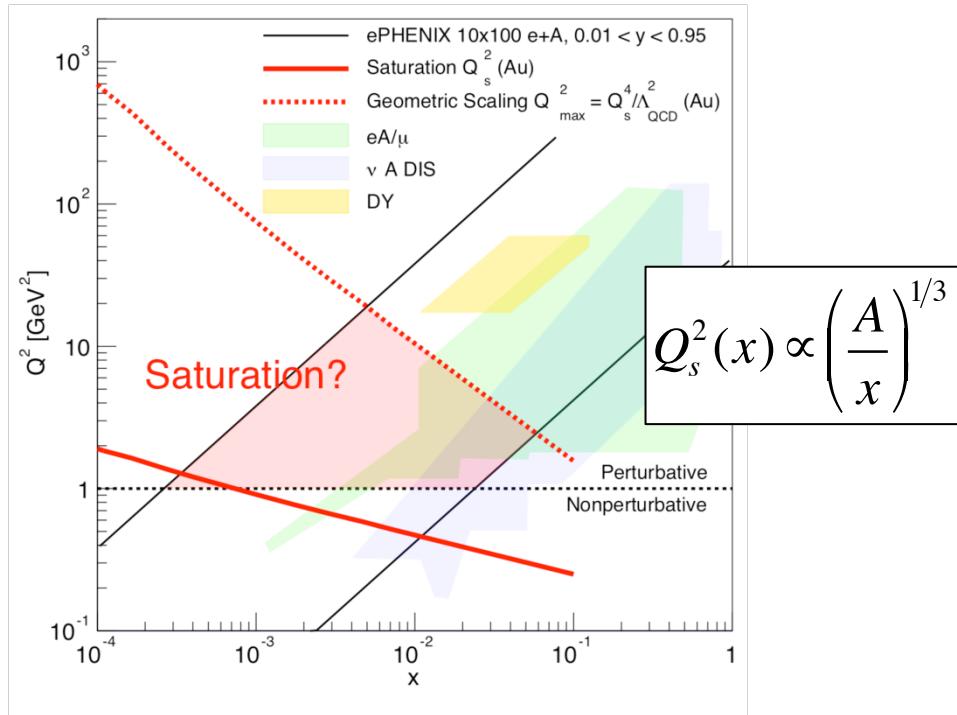
Precise imaging requires higher e-beam energy and luminosity

ePHENIX with its EMCal and tracking coverage is expected to do similar job (e.g with DVCS)

ePHENIX capabilities for these measurements – similar to generic EIC detector



Gluon Saturation



ePHENIX with its HCal and EMCAL coverage is expected to do similar job with **diffractive measurements**

Diffractive processes are most sensitive to gluon densities $\sim (xG)^2$



Color Glass Condensate (CGC)

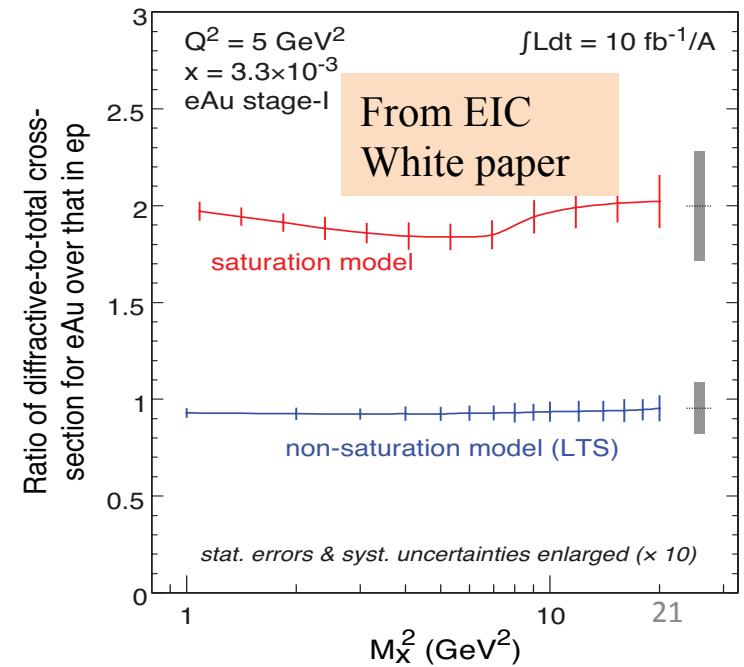
High gluon density matter

Direct consequence of gluon self-interaction in QCD

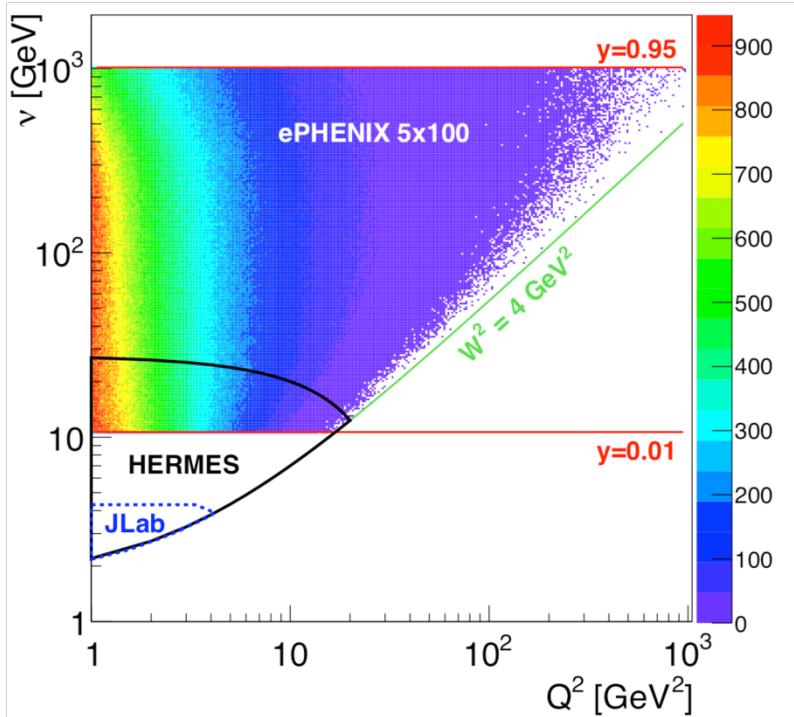
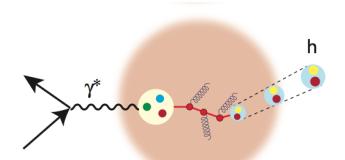
Saturation effects are greatly enhanced in eA collisions:

Collider energy \rightarrow low x

Heavy Ions \rightarrow high A



Hadronization



ePHENIX with its excellent hadron PID, at eRHIC with its high luminosity and wide kinematic reach, is expected to provide much smaller uncertainties in wider range of v , Q^2 and nucleus size



Semi-inclusive eA

Probe color neutralization and hadronization

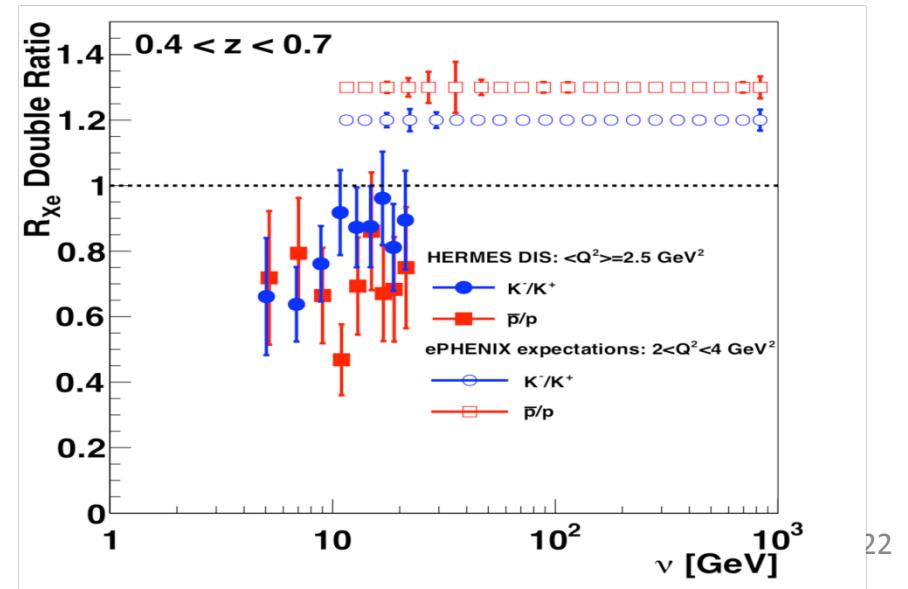
Different time&distance probed by varying nuclear size and parton energy

Previous experiments are limited by low v , Q^2
eRHIC:

Much larger range of v , Q^2

Wide range of nuclear size

Excellent ePHENIX hadron PID up to 60 GeV



Summary

ePHENIX will address a broad range of exciting EIC physics program, that will dramatically advance our understanding of how QCD binds nucleon and forms nuclear matter

Backup

BaBar Magnet



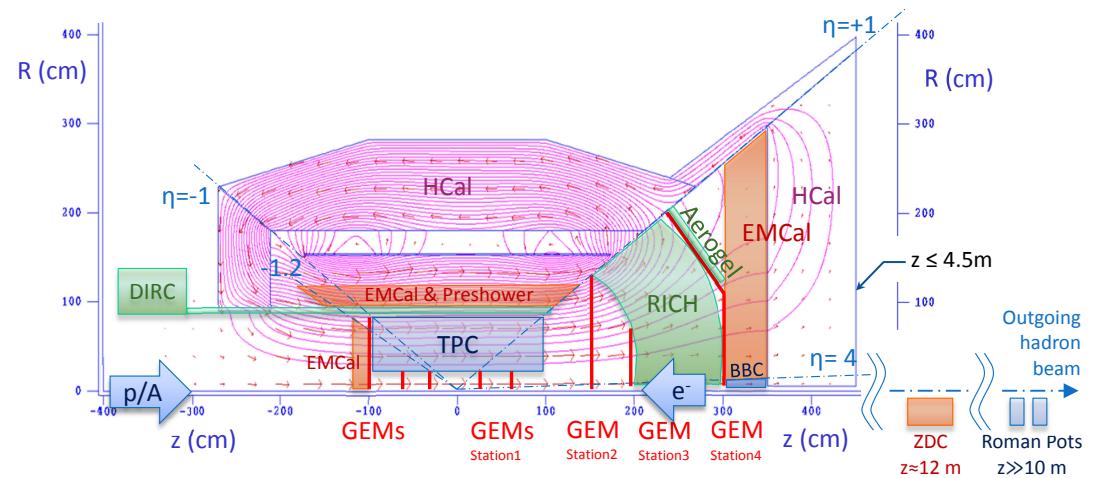
Major Parameters:

- ✓ Superconducting Solenoid
- ✓ Field: 1.5T
- ✓ Inner radius: 140 cm
- ✓ Outer radius: 173 cm
- ✓ Length: 385 cm

Higher current density at magnet ends and field shaping in forward angles provide **high analyzing power for momentum determination in e-going and h-going directions**

Flux return and field shaping:

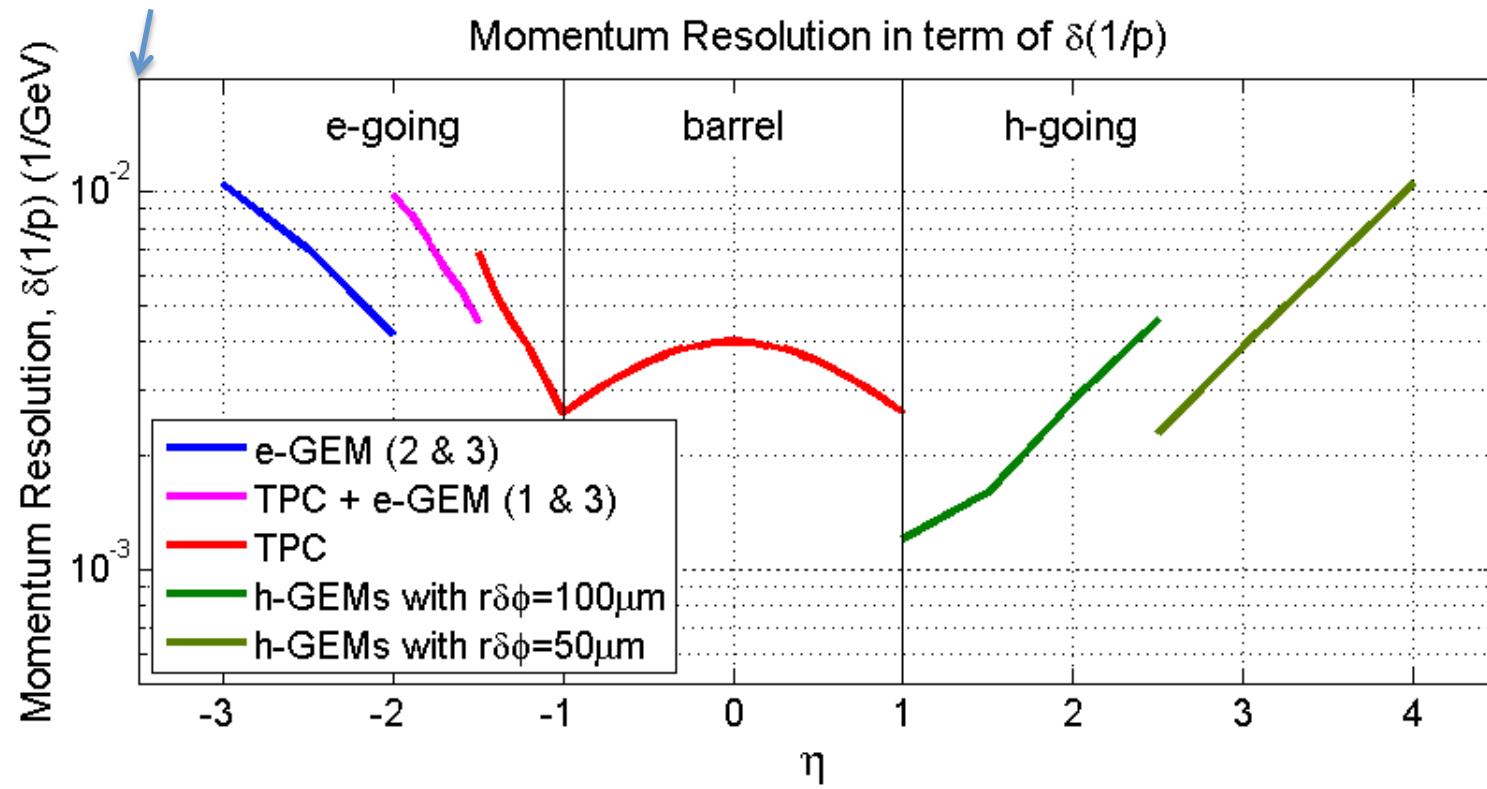
- Forward HCal
- Steel lapmshade
- Barrel HCal
- Steel endcup



Main space limitation observed: $|z| < 4.5\text{m}$
(due to focusing magnet location)

Momentum Resolution

$$\delta p/p \sim a \times p$$

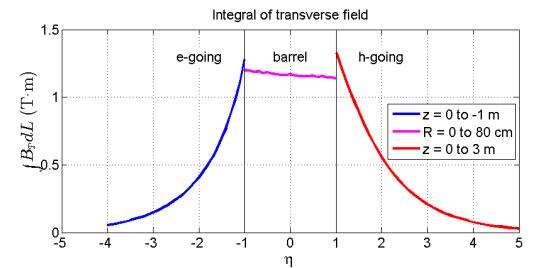


Good resolution over full tracking acceptance ($-3 < \eta < 4$)

e-going, $\sigma_p/p \sim (0.4-1.0\%) \times p$: primarily needed for electron ID (E/p)

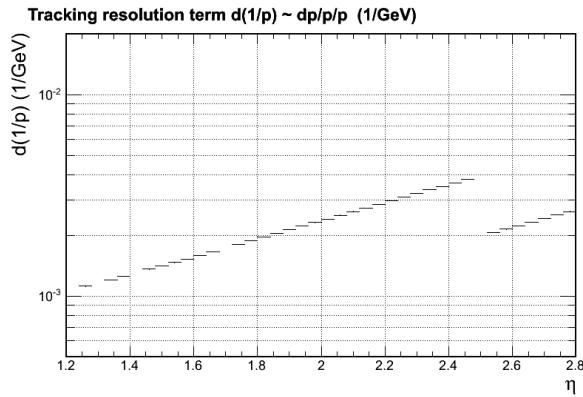
barrel, $\sigma_p/p \sim 0.4\% \times p$: hadron momentum, electron momentum at $p < 10 \text{ GeV}/c$

h-going, $\sigma_p/p \sim (0.1-1.0\%) \times p$: crucial for PID

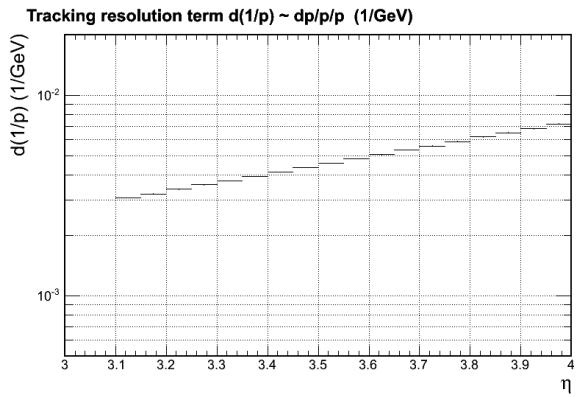


Momentum resolution: GEANT4

$1 < \eta < 3$



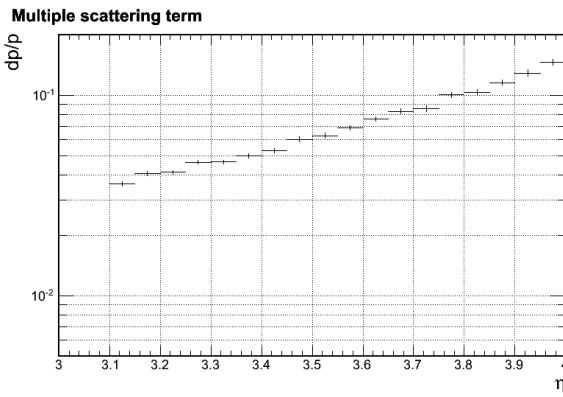
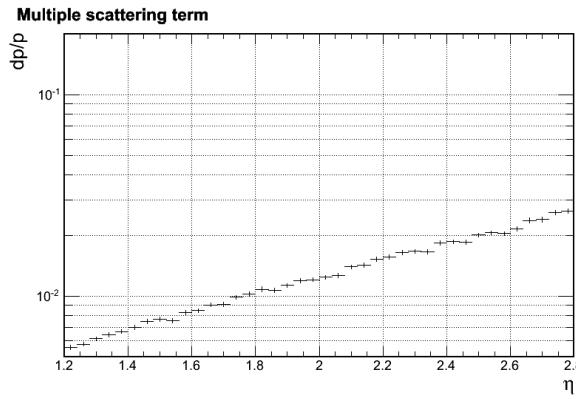
$3 < \eta < 4$



Tracker resolution term,
assuming fixed resolution on sagitta:

$1 < \eta < 2.5$: $d(\text{Sagitta}_2) = 120\mu\text{m}$ for $100\mu\text{m}$ tracker resolution

$2.5 < \eta < 4$: $d(\text{Sagitta}_2) = 60\mu\text{m}$ for $50\mu\text{m}$ tracker resolution



Multiple scattering term
Without RICH

TPC

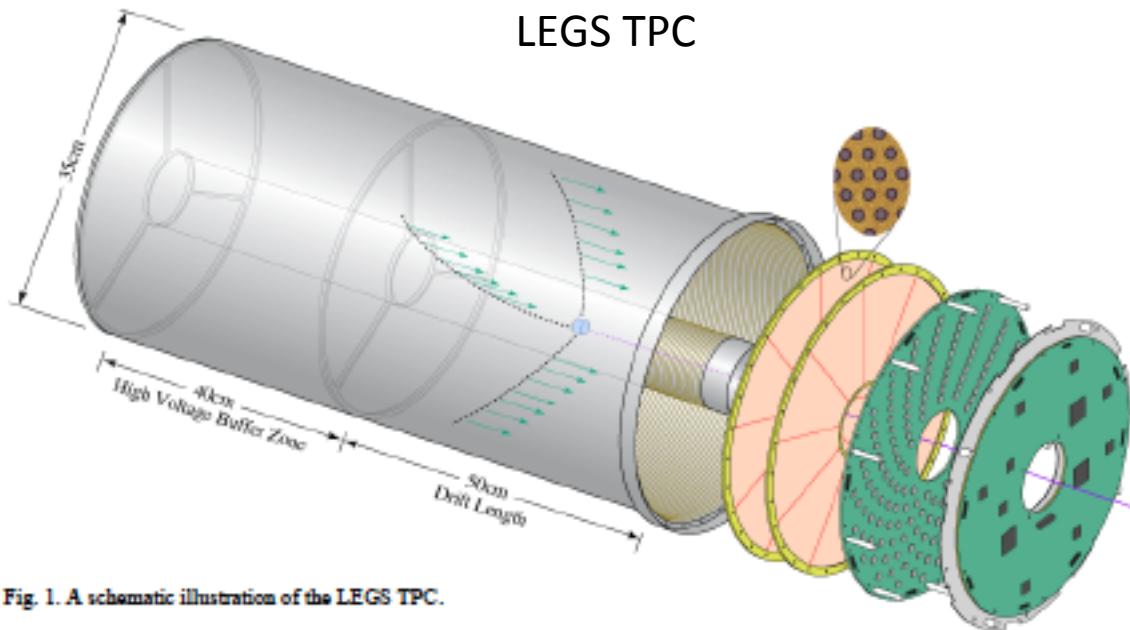
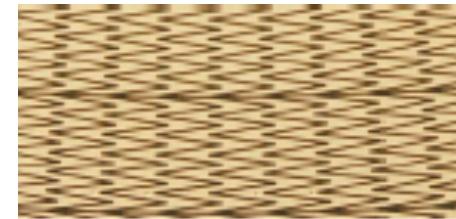


Fig. 1. A schematic illustration of the LEGS TPC.

Chevron-type readout pattern
with a pad size 2mm × 5mm

Achieved pos. res. 200 μm



ePHENIX TPC:

R=15-80cm, |z|<95cm

Gas mixture with fast drift time: 80% Ar, 10% CF₄, 10% CO₂

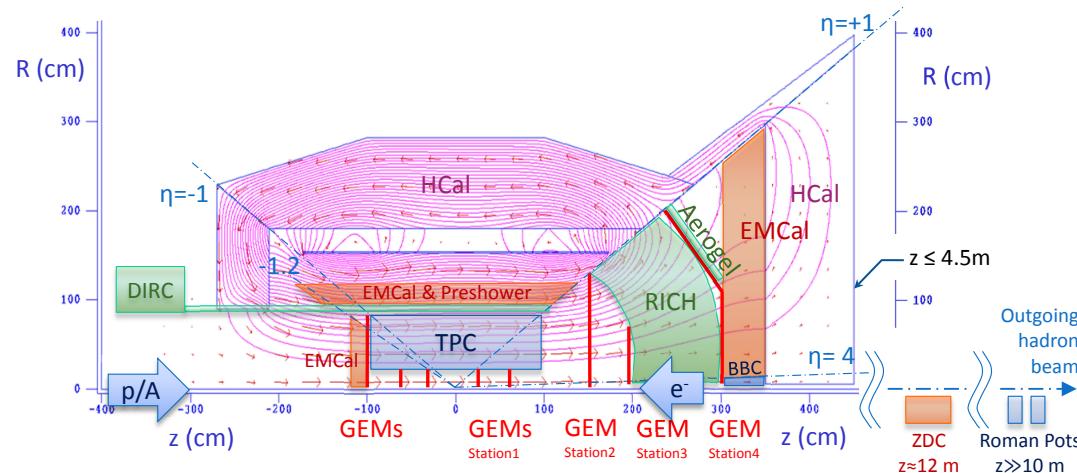
For 650 V/m → 10cm/μs → Drift time 10 μs

2×10mm pads → 180k pads (both ends readout)

Pos. resolution 300 μm (twice longer drift distance than LEGS)
and 40 readout rows => $\sigma_p/p \sim 0.4\% \times p$

Tracking with GEM

Improved pos. res.
with mini-drift GEM



e-going direction

Station 1-2: $z=30, 55\text{cm}$ $r=2-15\text{cm}$

Station 3: $z=98\text{ cm}$

$-3 < \eta < -2$: $50\mu\text{m}$ with 1mm pad

$-2 < \eta < -1$: $100\mu\text{m}$ with 2mm pad

$\Delta r=1\text{cm}$ for St1-2 and $\Delta r=10\text{cm}$ for St3

h-going direction

Station 1: $z=17$ and 60cm with $r=2-15\text{cm}$

Station 2-4: $z=150, 200, 300\text{ cm}$, $1 < \eta < 4$

$2.5 < \eta < 4$: $50\mu\text{m}$ with 1mm pad

$1 < \eta < 2.5$: $100\mu\text{m}$ with 2mm pad

$\Delta r=1-10\text{cm}$

Collision vertex is necessary in e-going direction:

BBC: $\eta=4-5$, $z=3\text{m}$, $\sigma_t=30\text{ps}$ (with MRPC or MCP) ->
 $\sigma_z=5\text{mm}$ -> const term in $\sigma_p/p \sim 2\%$

Total channel count: 217k

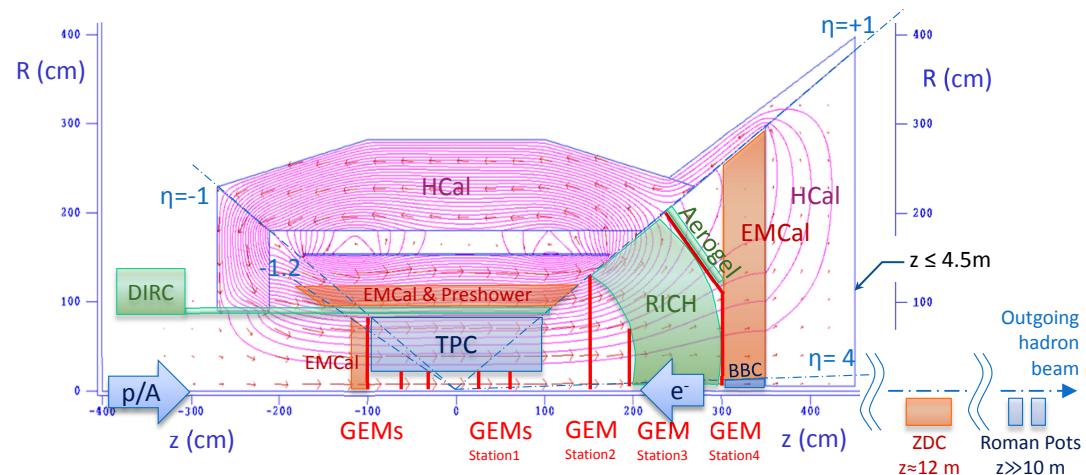
Large area GEMs are being developed in CERN for CMS (needed for our St 2-4)

Calorimetry

EMCal coverage $-4 < \eta < 4$

HCal coverage $-1 < \eta < 5$

Readout: SiPM



e-going direction

Crystall EMCal:

$2\text{cm} \times 2\text{cm}$

5k towers

$\sigma_E/E \sim 1.5\%/\sqrt{E}$

$\sigma_x \sim 3\text{mm}/\sqrt{E}$

Barrel (sPHENIX)

Tungsten-fiber EMCal:

$2\text{cm} \times 2\text{cm}$

25k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

Steel-Sc HCal:

$10\text{cm} \times 10\text{cm}$

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

h-going direction

Pb-fiber EMCal:

$3\text{cm} \times 3\text{cm}$

26k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

Steel-Sc HCal:

$10\text{cm} \times 10\text{cm}$

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

Hadron PID

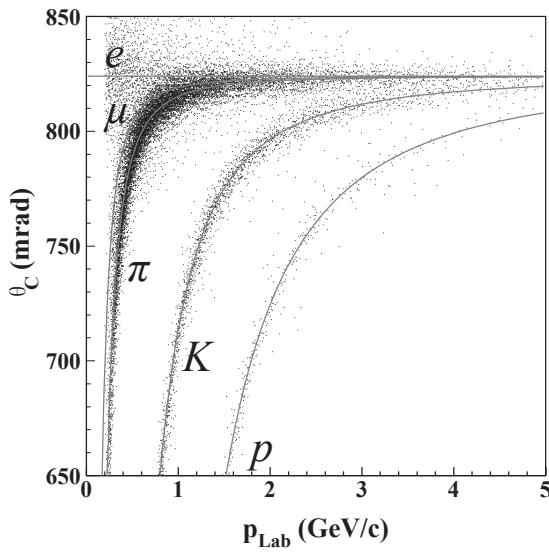
DIRC

$-1 < \eta < 1$

Mirror focusing ?

Threshold for $\pi/K/p$:

0.2/0.7/1.5 GeV



Gas RICH (CF4)

$1 < \eta < 4$

Mirror focusing

Threshold for $\pi/K/p$:

4/15/29 GeV

6 azimuthal segments

Photodetection: GEM with CsI

Area $6 \times 0.3 \text{ m}^2 \rightarrow 220 \text{ k ch}$

In gas volume!

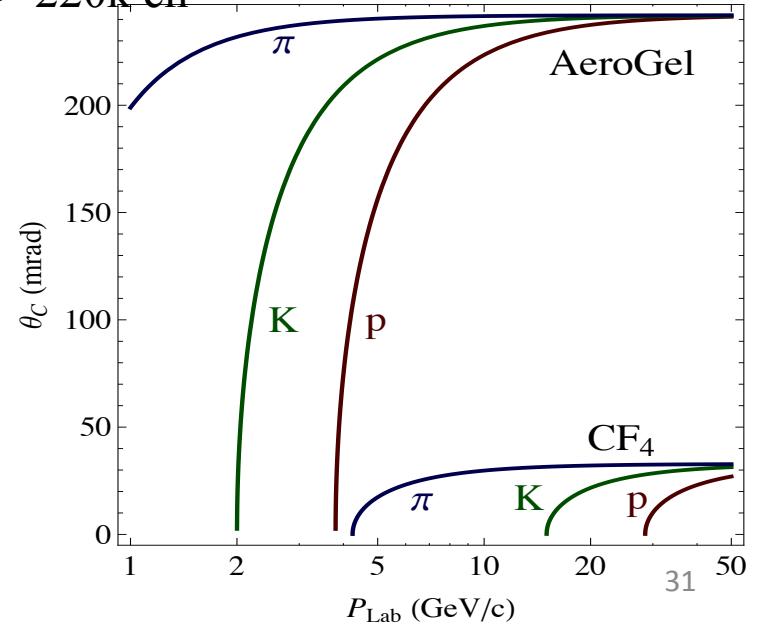
Aerogel

$1 < \eta < 2$

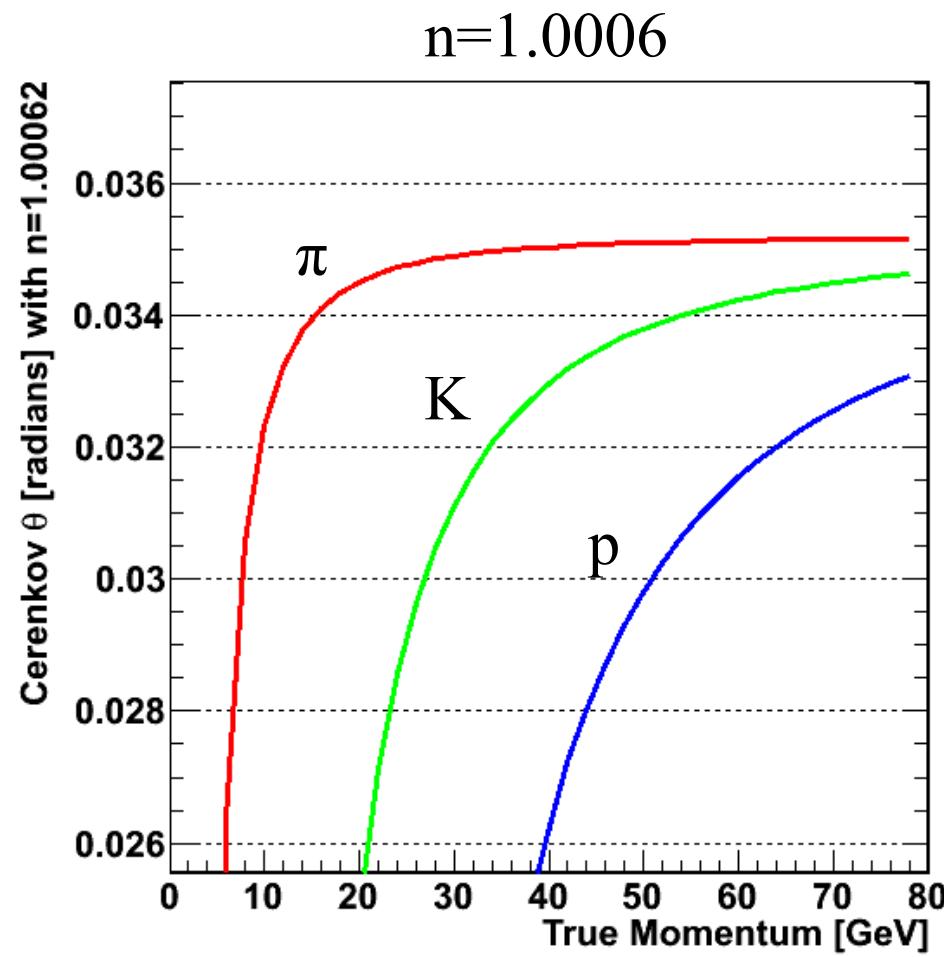
Proximity focused

Threshold for $\pi/K/p$:

0.6/2/4 GeV



Cerenkov Angle in CF4



Hadron PID: gas RICH

Goals and assumptions/restrictions

1m gas volume along the track => $F=1\text{m} \Rightarrow R=2\text{m}$

$Z > 1.5\text{m}$ (optimal sagitta plane)

$Z < 3.0\text{m}$ (EMCal)

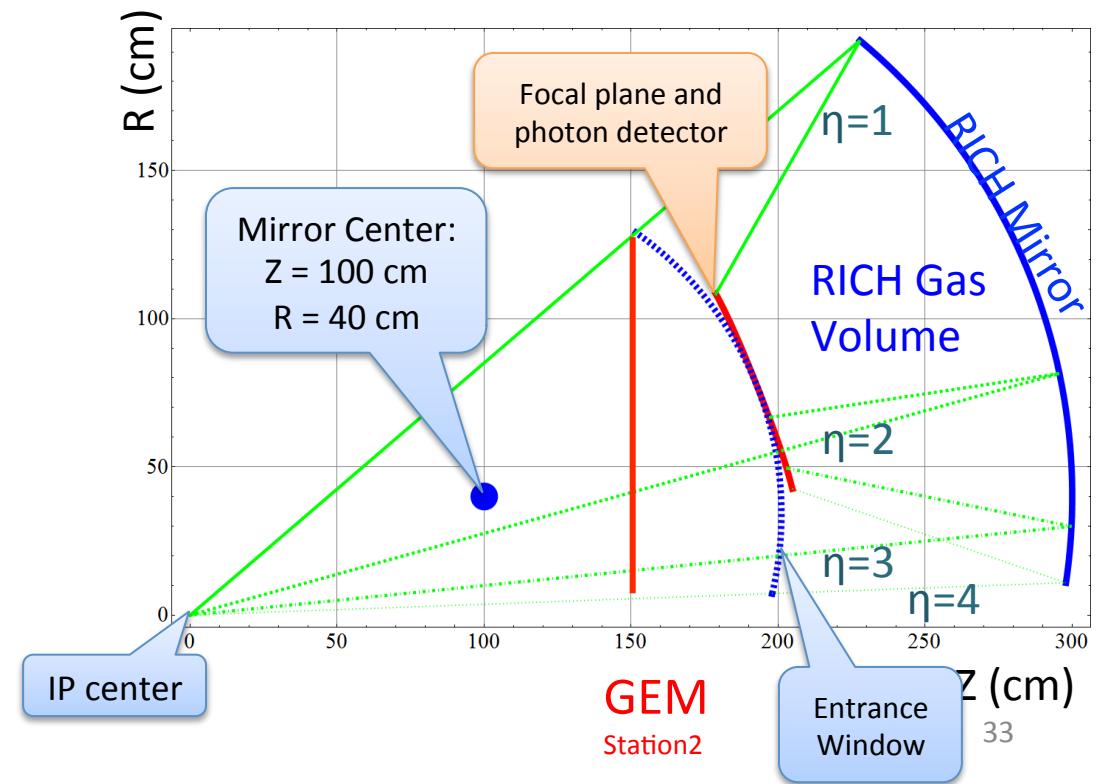
Photon detector inside tracking volume → GEM as thin → flat

Low number of edges between mirrors

Small area for photon readout

Moving mirror center to beam line:

- Focal plane not flat
- Steeper impact angle on the photon detector
- Photon detector closer to beam line
- RICH volume moves to $z < 1.5\text{m}$



Hadron PID: gas RICH

CF4 ($n=1.00062$)

Ring resolution

Ring radius resolution: $2.5\%/\sqrt{N_\gamma}$

From current EIC R&D studies

LHCb and COMPASS claimed 1% per photon

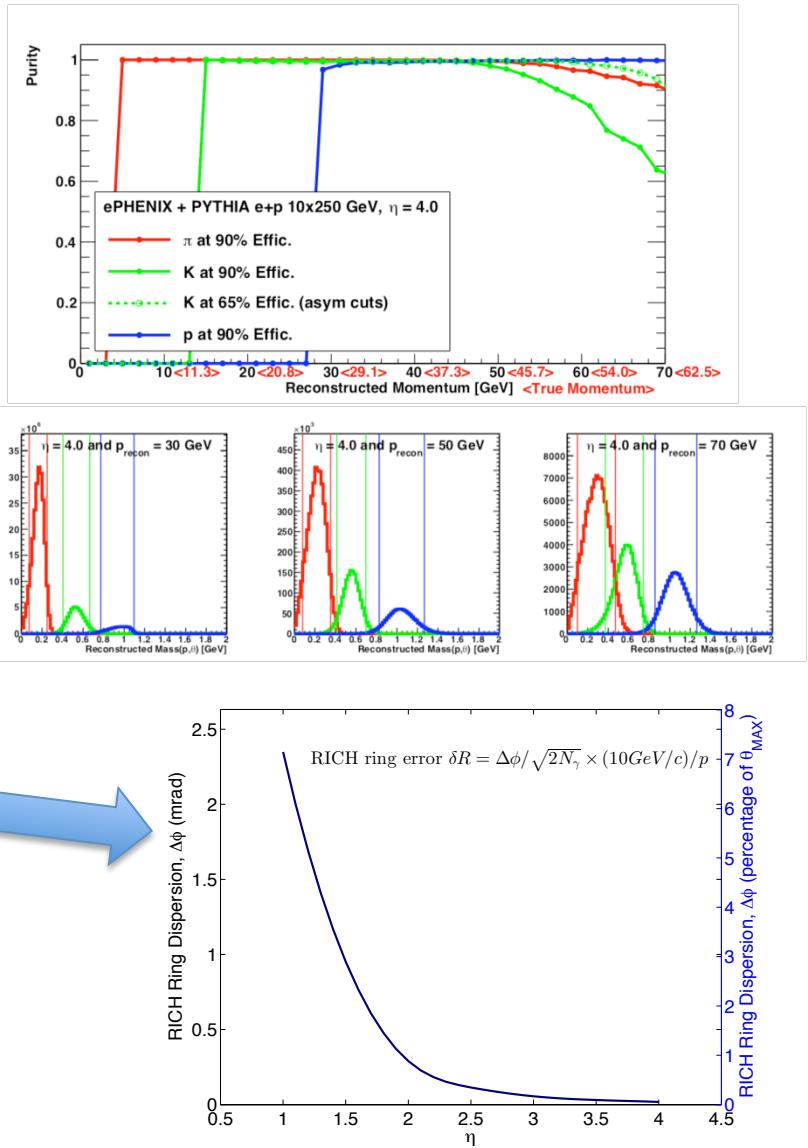
Residual magnetic field (~ 0.5 T) bends tracks radiating photons \Rightarrow ring smearing

Since field is near parallel to tracks the effect is minimal

Off-center vertex tracks have shifted focal plane \Rightarrow ring smearing

For $\eta=1$ and $z=40\text{cm}$ \Rightarrow ring dispersion $5\%/\sqrt{N_\gamma}$

For larger η effect is smaller



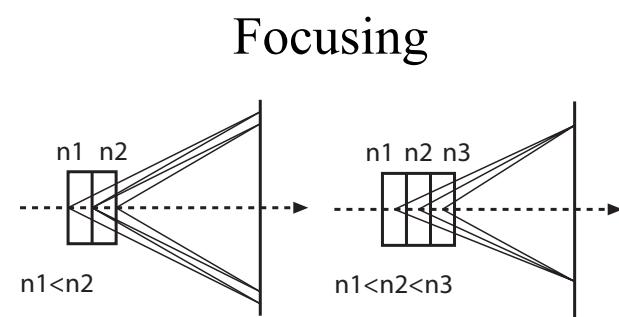
Ring resolution limits PID at higher p^{34}

Hadron PID: Aerogel

Allows to identify K for $3 < p < 10$ GeV

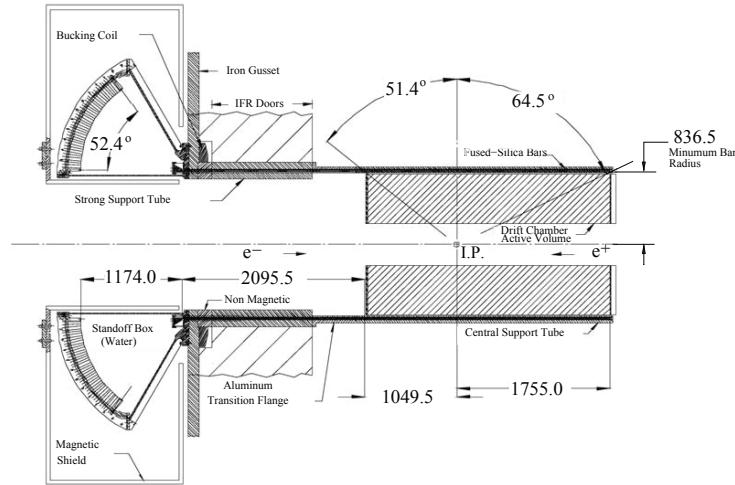
Challenges:

- Fringe field
- Low light output
- Visible wavelength range
- Limited space for light focusing



Photon detection:
Microchannel Plate Detector
Multi-alkali photocathode
Also ToF with $\sigma=20-30$ ps
Being developed by
LAPPD Collaboration

Hadron PID: DIRC

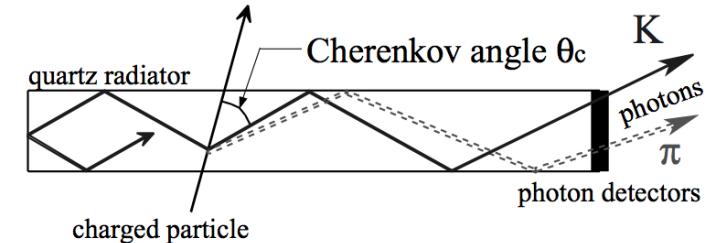


BaBar DIRC

Quartz radiator bars, Cerenkov light internally reflected

No focusing => Large water filled expansion volume

PMT for readout



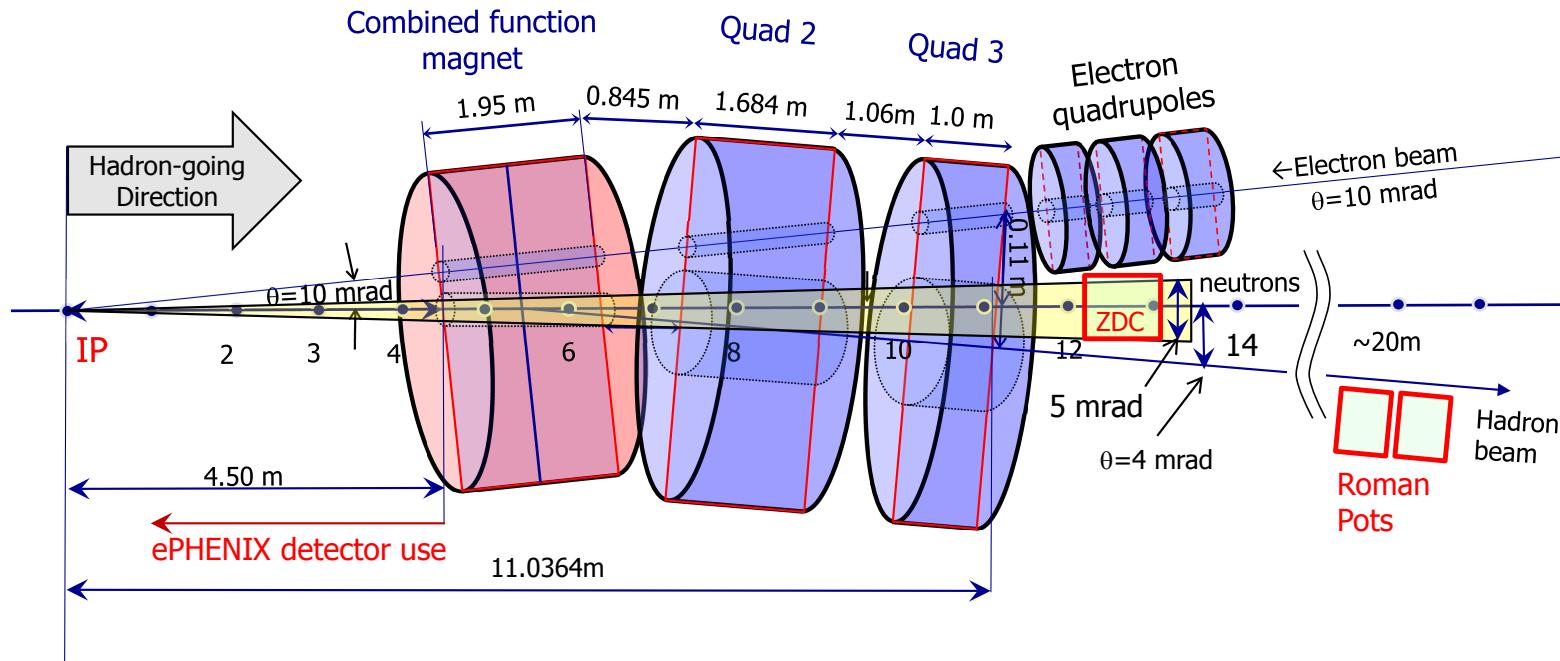
ePHENIX DIRC

Mirror Focusing to avoid large expansion region

Pixelated multi-anode PMT for readout

Ring resolution limits PID at higher p_T

Beamline Detectors



ZDC

12 m downstream

5 mrad cone opening of the IP is available from ePHENIX and IP design

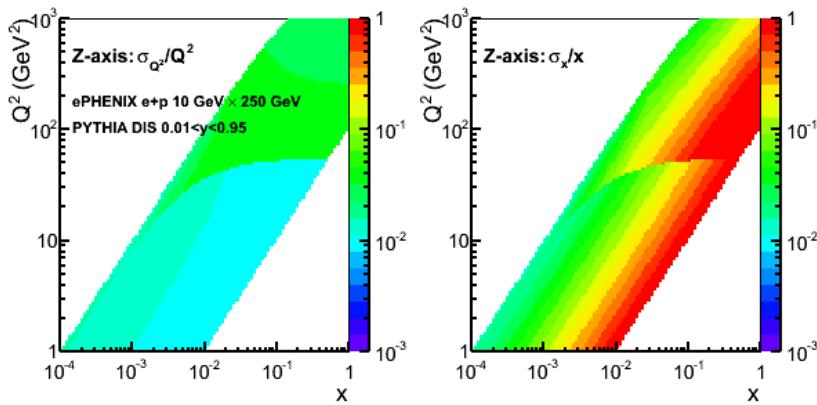
Roman Pots

>20 m downstream

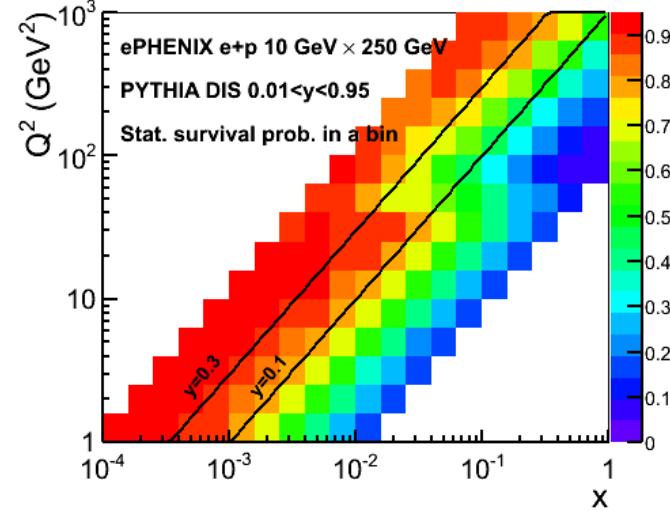
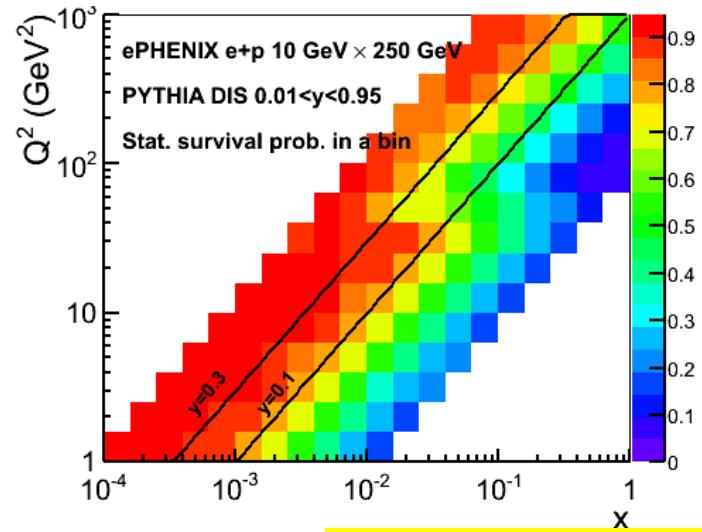
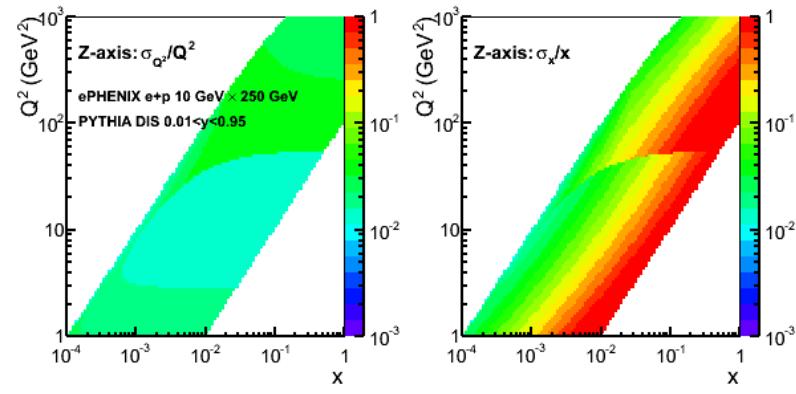
Similar to STAR design

DIS kinematics: angle from EMCAL

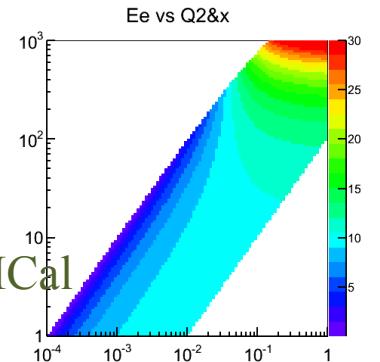
With perfect angle measurements



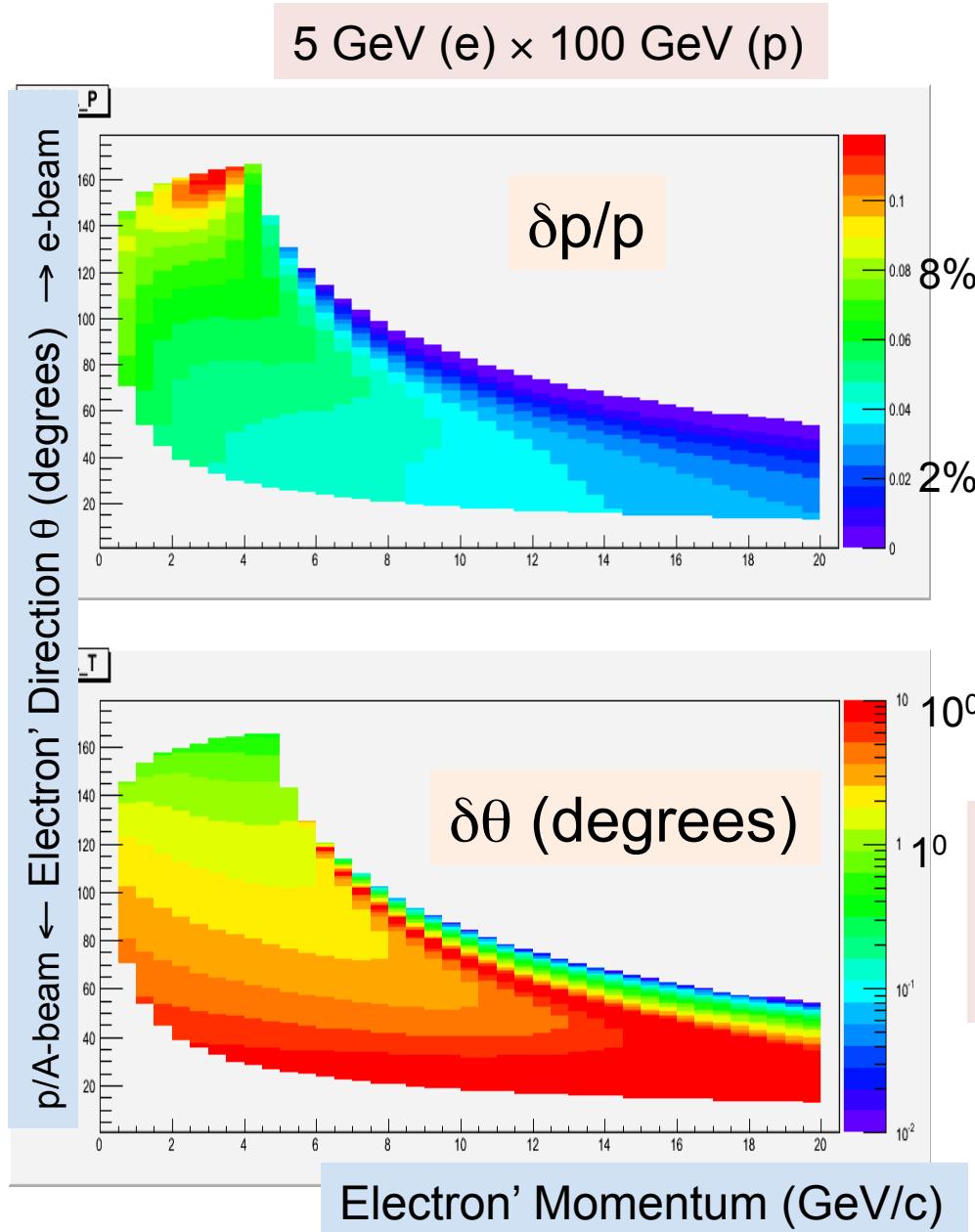
With angle smearing due to EMCAL pos. resolution



Only minor effect from angle measurements with EMCAL



Tom H: Momentum and angle resolution



Inclusive measurements:

$$\sigma_{red} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

$$(x, Q^2) \rightarrow (p, \theta)_e$$

Resolution \rightarrow Systematics \rightarrow Unfolding

Assume: $\sigma_{syst} \sim 1/5$ of systematics

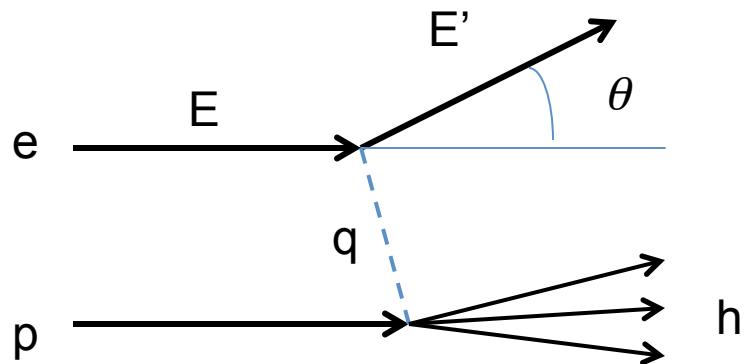
0.1×0.1 binning in $\log_{10}(x) \times \log_{10}(Q^2)$

Require: 1% uncertainty in each bin

“Reasonable” resolutions may be enough:

$\delta p/p \sim 2-8\%$

$\delta\theta \sim 1$ degree



Electron vs Jacquet-Blondel

Electron

$$Q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E} \cos^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

JB

$$Q_{JB}^2 = \frac{p_{T,h}^2}{1 - y_{JB}}$$

$$p_{T,h}^2 = \left(\sum_h p_{x,h} \right)^2 + \left(\sum_h p_{y,h} \right)^2$$

$$y_{JB} = \frac{(E - p_z)_h}{2E_e}$$

$$(E - p_z)_h = \sum_h (E_h - p_{z,h})$$

$$x_{JB} = \frac{Q_{JB}^2}{sy_{JB}}$$

$y \rightarrow 0$: $\sigma_y/y \sim 1/y$

$y \rightarrow 0$: $\sigma_y/y \sim \text{const}$

JB

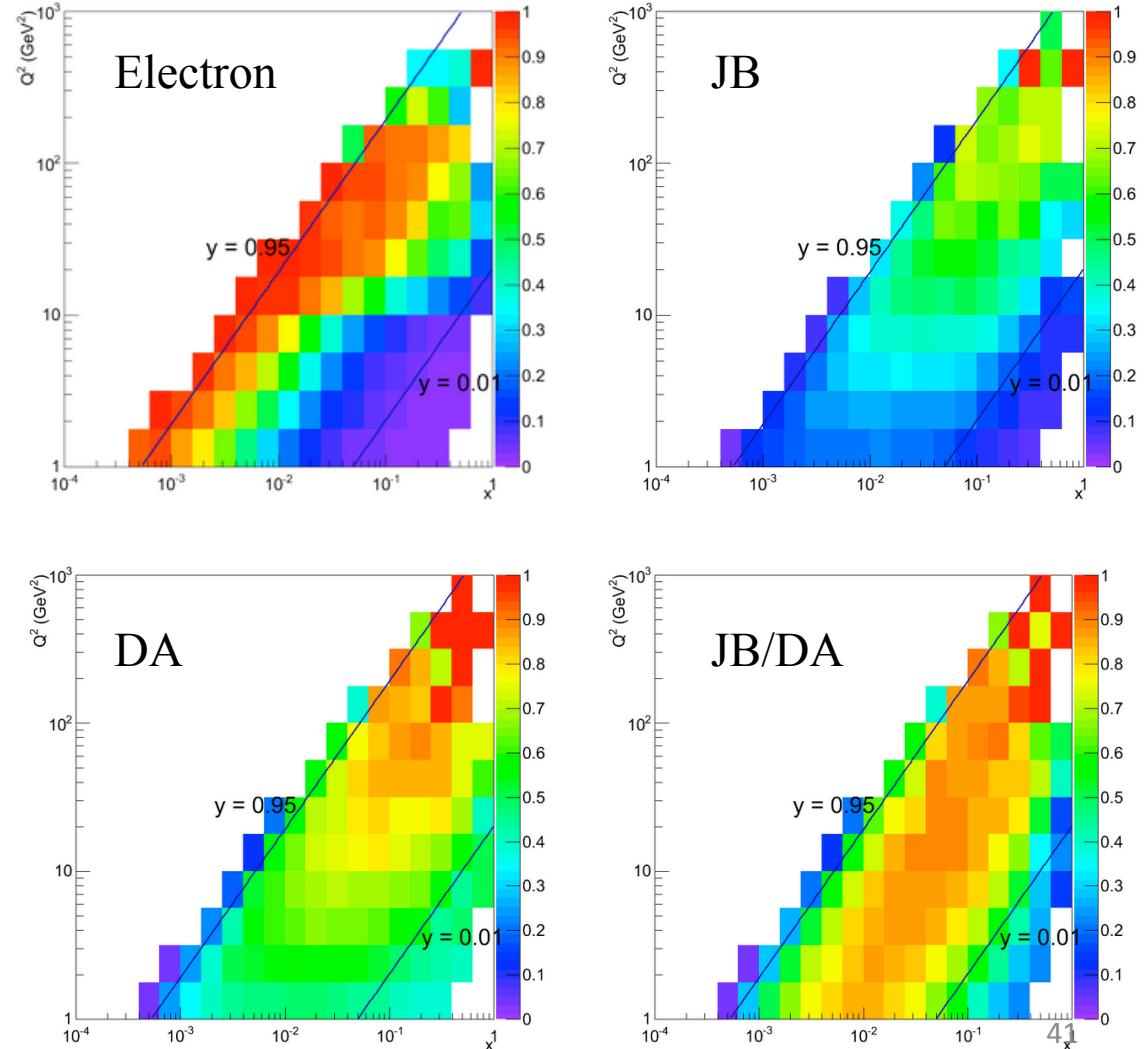
EIC group studies:

https://wiki.bnl.gov/eic/index.php/Q2-x_bin_migration

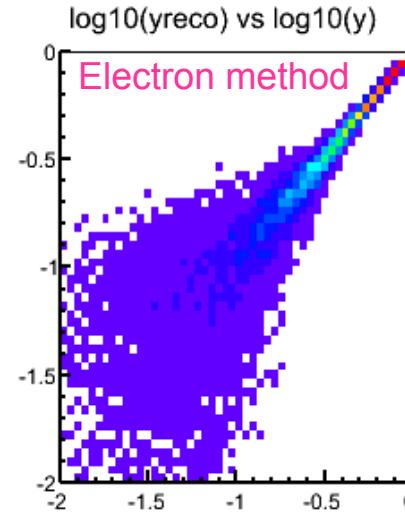
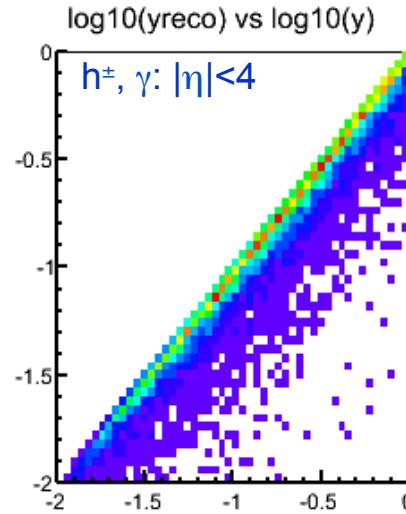
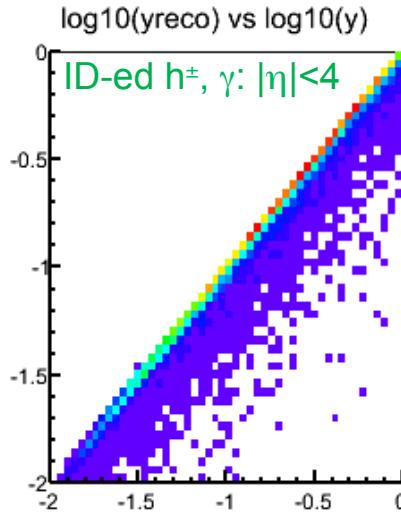
JB and DA methods give better resolution at lower y and higher Q^2

Our studies:

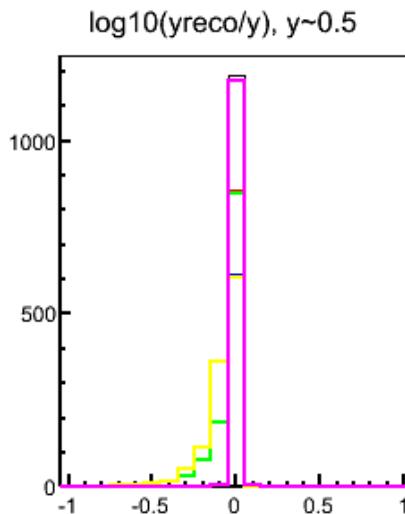
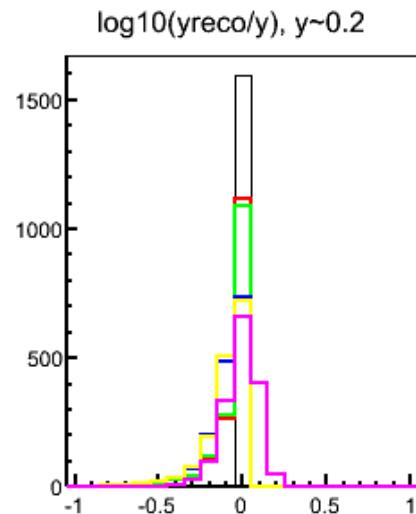
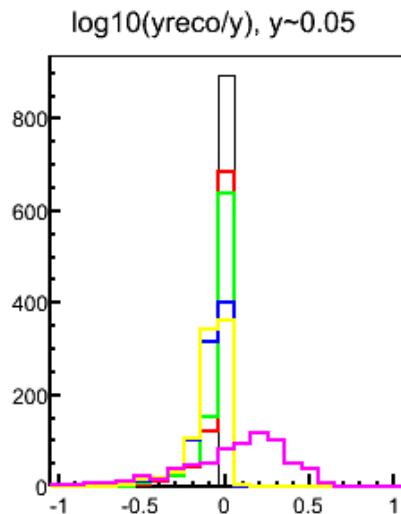
- Enough to measure hadrons in $|\eta|<4$
- Hadron PID is important
 - Particularly for lower Q^2
- For $y<0.2$ – enough to measure in $-1<\eta<4$
 - The acceptance we'll equip with hadron ID



JB: 5x100 Q₂>10



- Enough to measure hadrons in $|\eta| < 4$
- Hadron PID is important
Particularly for lower Q^2
- For $y < 0.2$ – enough to measure in $-1 < \eta < 4$
The acceptance we'll equip with hadron ID

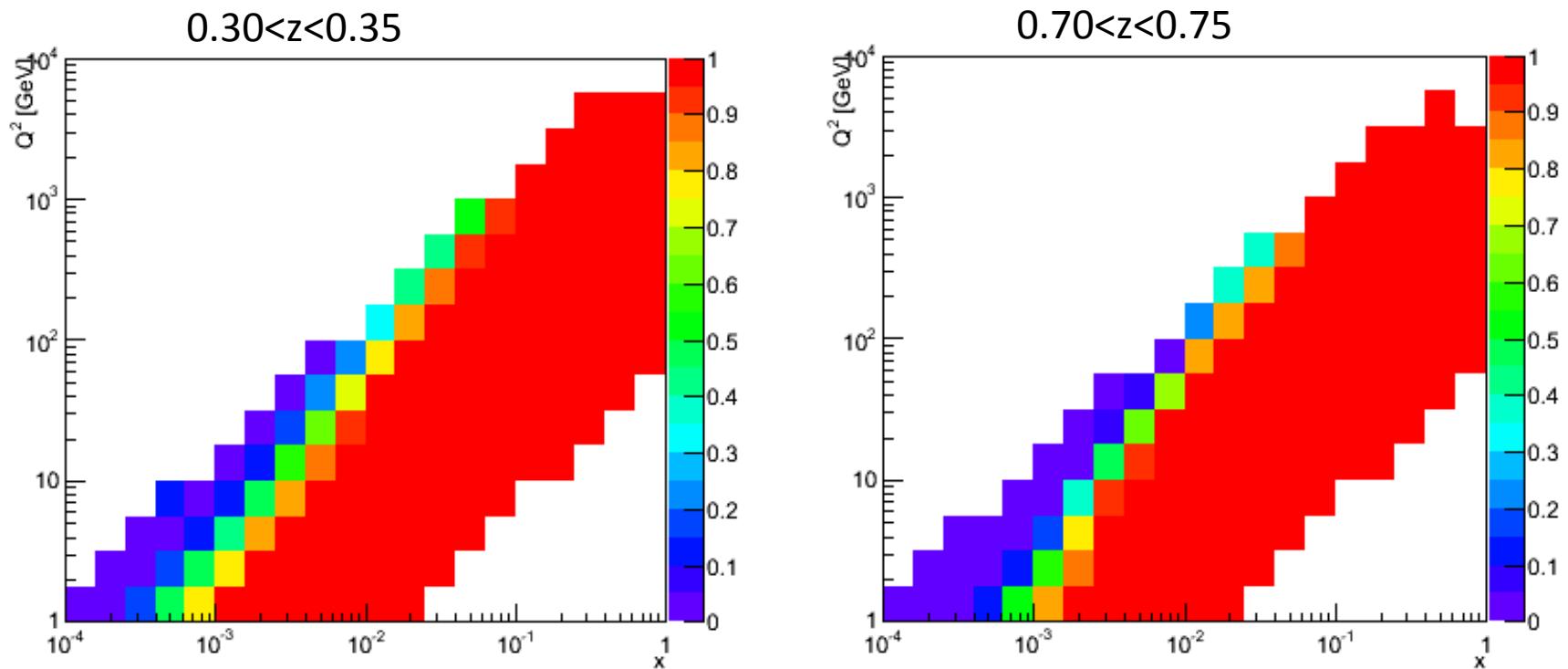


All
 ID-ed h^\pm, γ
 ID-ed $h^\pm, \gamma: |\eta| < 4$
 $h^\pm, \gamma: |\eta| < 4$
 $h^\pm, \gamma: |\eta| < 4, p$ -smeared
 Electron method

Green ~ Red
 Blue ~ Yellow

(x, Q^2) loss due to no PID in e-going direction

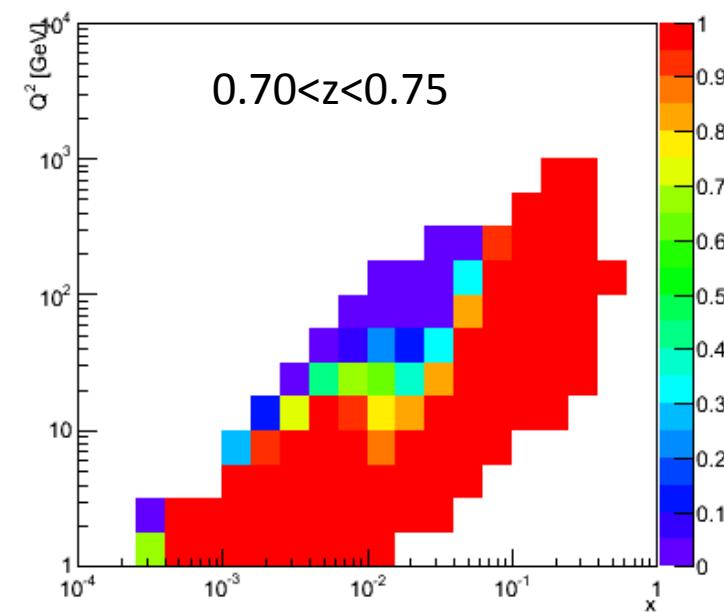
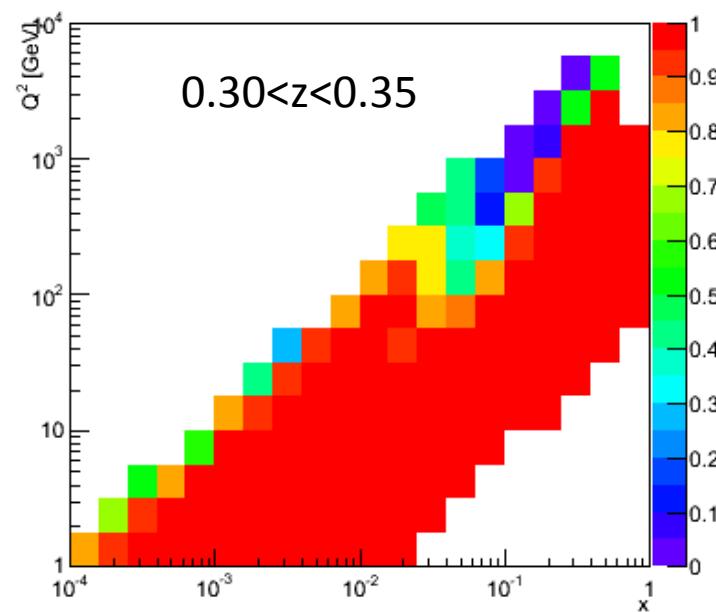
e+p 10 GeV \times 250 GeV
PYTHIA DIS $0.01 < y < 0.95$ $W^2 > 10 \text{ GeV}^2$



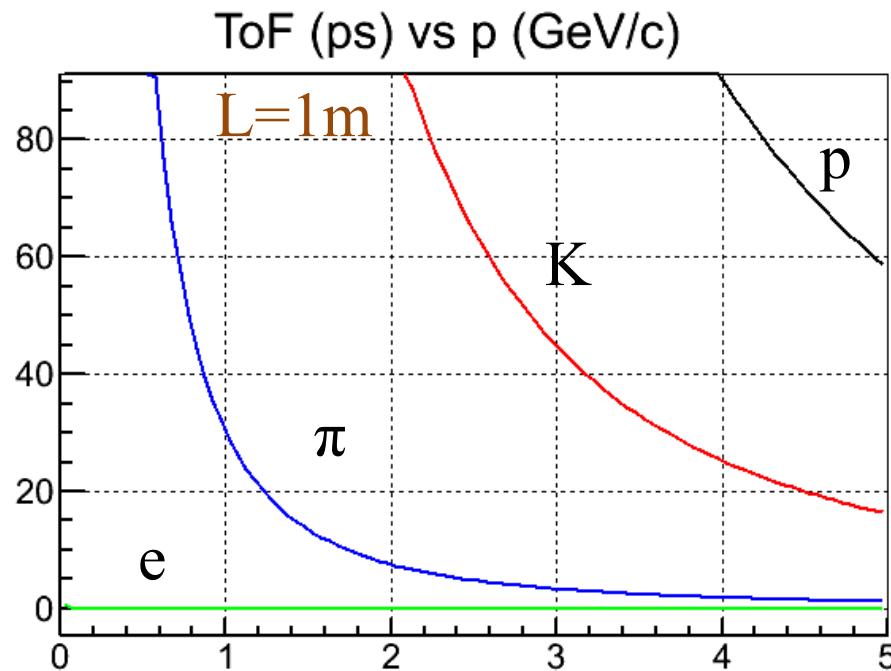
If better DIRC?

e+p 10 GeV \times 250 GeV
PYTHIA DIS $0.01 < y < 0.95$ $W^2 > 10$ GeV 2

“Normal” DIRC: π/K separation up to 3.5 GeV/c
Improved DIRC: π/K separation up to 6 GeV/c



ToF for PID?



With 10 ps resolution including t_0 :

e/ π separation at $<1 \text{ GeV}/c$

K/ π separation at $<4 \text{ GeV}/c$

Need t_0 ($\sigma < 10\text{ps}$) and vertex ($\sigma \sim 1\text{mm}$)

Cost and schedule

Table 4.1: Estimated equipment costs for the ePHENIX detector (in \$M).

		Cost	Overhead	Contingency	Total
Calorimeters	Endcap Crystal	3.40	0.47	1.93	5.80
	Forward EMCAL	1.41	0.27	0.84	2.53
	Forward HCAL	3.90	0.68	2.29	6.87
Tracking	TPC	0.75	0.19	0.47	1.41
	GEM Trackers	0.71	0.18	0.44	1.33
Beamline instrumentation	Roman pots	0.23	0.04	0.14	0.41
	Beam-Beam counter	0.20	0.05	0.13	0.38
Particle ID	DIRC	12.50	1.75	7.13	21.38
	RICH	2.00	0.50	1.25	3.75
	Aerogel	1.55	0.22	0.88	2.65
Electronics/sensors	Endcap Crystal	0.89	0.22	0.56	1.67
	Forward EMCAL	3.09	0.43	1.76	5.28
	Forward HCAL	0.38	0.05	0.22	0.65
	TPC	2.80	0.81	1.81	5.42
	GEM Trackers	0.71	0.18	0.44	1.33
	DIRC	0.77	0.19	0.48	1.44
	RICH	0.69	0.17	0.43	1.29
	Aerogel	1.55	0.39	0.97	2.91
	Roman Pots	0.11	0.03	0.07	0.21
	Beam-Beam	0.10	0.02	0.06	0.19
	Data Collection	0.60	0.15	0.38	1.13
Integration/Mechanical	Trigger	0.60	0.15	0.38	1.13
		3.00	0.93	1.96	5.90
Total		41.94	8.08	25.01	75.02

Table 4.2: Total estimated labor for ePHENIX detector construction.

	FY21	FY22	FY23	FY24	Total
Physicist FTE	10	9	10	13	42
Physicist cost	3.02	2.78	3.45	4.60	13.85
Engineer FTE	10	10	7	5	31
Engineer cost	2.59	2.66	2.02	1.49	8.76
Technician FTE	1	1	11	19	31
Technician cost	0.21	0.21	2.29	4.16	6.87
Total FTE	20	19	28	37	104
Total cost	5.81	5.65	7.77	10.25	29.49

Table 4.3: Schedule of Critical Decisions and reviews necessary for construction FY2021–FY2024.

CD0	4Q2016
CD1 review	4Q2017
TDR preparation	4Q2017 - 3Q2019
CD2/3 review	4Q2019
FY2021 budget briefing	1Q2020
Construction start	4Q2020 (FY2021)
CD4	3Q2024 (FY2024)
Commissioning run	1Q2025